

# **Environmental Exposure Effects on Historic Stone Building**

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## Table of Contents

|   |    |
|---|----|
| List of Figures.....  | 2  |
| List of Tables.....   | 2  |
| 1. Introduction.....  | 3  |
| 2. Methods.....   | 4  |
| 2.1 FLUENT modeling.....  | 4  |
| 2.2 Wind Tunnel Tests.....  | 5  |
| 2.3 Field Experiments.....  | 6  |
| 3. Field Experiments.....   | 7  |
| 3.1 Measurement of Horizontal Rain Fluxes.....                                | 7  |
| 3.2 Collection of Meteorological Data.....                                    | 7  |
| 3.3 Maintenance of Equipment.....   | 8  |
| 4. Results of Field Experiments.....  | 9  |
| 4.1 Meteorological Data.....  | 9  |
| 4.2 Horizontal Rain Flux Data.....  | 9  |
| 5. Discussion.....  | 10 |
| 5.1 Comparison of Meteorological Data.....                                    | 10 |
| 5.2 Interpretation of Meteorological Data.....                                | 11 |
| 5.3 Correlation between Meteorological Data and Rain Flux Data.....           | 12 |
| 6. Future Work.....   | 14 |
| References.....   | 15 |
| Appendix A Soiling Patterns on a Tall Limestone Buildings: Changes over Sixty |    |
| Appendix B Changes of Soiling Patterns over Time on the Cathedral of Learning |    |
| Appendix C Impingement of Rain Drops on a Tall Building                       |    |

## List of Figures

|  |    |
|--|----|
| Figure 3.1 Experimental apparatus for measuring rain fluxes.....   | 16 |
| Figure 3.2 Rain flux measurement locations on the Cathedral.....   | 17 |
| Figure 3.3 Different soiling patterns at each location.....  | 18 |
| Figure 3.4 Weather station on the roof of Warner Hall at CMU.....  | 22 |
| Figure 5.1 Comparison of wind direction data during 7/16/99 - 7/31/99.....   | 23 |
| Figure 5.2 Comparison of wind speed data during 7/16/99 - 7/31/99.....   | 24 |
| Figure 5.3 Comparison of cumulative rainfall during 7/16/99 - 7/31/99.....   | 25 |
| Figure 5.4 Cumulative rainfall for the period 7/24/99 - 9/30/99.....   | 26 |
| Figure 5.5 Meteorological conditions during rainy periods for 7/24/99 - 9/30/99.....   | 27 |
| Figure 5.6 Meteorological conditions during rainy periods for 7/24/99 - 9/30/99<br>(without one severe storm interval on 8/24/99)..... | 28 |
| Figure 5.7 Total rain water collected vs. total rainfall.....  | 29 |
| Figure 5.8 Correlation between meteorological data and rain flux data.....   | 30 |

## List of Tables

|   |    |
|---|----|
| Table 4.1 Meteorological data for intervals with rainfall.....        | 43 |
| Table 4.2 Horizontal rain fluxes during period 7/24/99 - 9/30/99..... | 52 |

## 1. Introduction

The damage to historic structures caused by anthropogenic air pollution has been widely reported. In order to preserve those structures and assist conservators' efforts, better understanding of the processes involved is necessary. The research conducted at the Cathedral of Learning has been oriented toward this purpose. The project has been divided into three phases. Phase I included on-site measurements of vertical profiles of pollutant concentrations and deposition fluxes, while Phase II has focused on computer modeling of airflow and wind-driven rain fluxes. Phase III will involve development of a comprehensive computer model for predicting soiling of structures by pollutants. We are currently in the middle of Phase II.

The results from Phase I showed that airborne concentrations and deposition of pollutants were roughly uniform with height. This was explained by hypothesizing well-mixed airflow around the building. We also hypothesized that raindrop impingement plays a very important role in the decrease of soiling on the Cathedral. Therefore, investigating airflow and wind-driven rain fluxes has become an important focus of current research.

This report summarizes the work conducted on the Cathedral of Learning project during the period October 1, 1998 to September 30, 1999. Following this introduction, Section 2 discusses computer modeling, preparation for wind tunnel tests, and a synopsis of the field experiments conducted. Section 3 describes in detail two field experiments - measurement of horizontal rain fluxes and collection of meteorological data. Data collected from both experiments are then presented in Section 4. Section 5 includes data validation and interpretation. Finally, Section 6 summarizes plans for future work. Appendix A is a revised manuscript that has been submitted for publication in *Environmental Science & Technology*. Appendix B is a manuscript submitted to Imperial College Press as a chapter in *The Effects of Air Pollution on The Built Environment*, edited by Peter Brimblecombe. Appendix C contains a revised manuscript accepted for publication in *Atmospheric Environment*.

## 2. Methods

In order to quantify surrounding airflow patterns and rain delivery to the walls of the Cathedral of Learning, we are using three approaches: computer modeling, wind tunnel tests, and field experiments. These three categories of work are now discussed.

### 2.1 FLUENT modeling

Our computer modeling efforts include two major tasks: modeling airflow around a simplified geometry of the Cathedral, and calculations of wind-driven rain fluxes to the building surfaces. Both efforts have been conducted by using FLUENT, a commercially available computational fluid dynamics software package (FLUENT Inc. Lebanon, NH).

During the modeling, the Reynolds-averaged Navier-Stokes and continuity equations are solved numerically to obtain the steady-state velocity field. Closure is achieved with the aid of the Re-Normalization Group K- $\epsilon$  (RNG) equations, where K is the turbulent kinetic energy and  $\epsilon$  is the turbulent kinetic energy dissipation. The flow field is computed at wind incidence angles of  $0^\circ$  and  $45^\circ$ . The computational domain is determined so that it can enclose the entire airfield affected by the building. The structured mesh for numerical calculation is constructed so that the density of nodes is highest near the building surfaces and ground.

At the top boundary, the side boundary, and the plane of symmetry, components of velocity and gradients of all flow variables in the direction normal to the boundary are set to zero. For the ground and the surfaces of the block, standard wall functions (Rodi, 1980) are used to calculate the source terms for K and  $\epsilon$ . On the upwind boundary (inlet), K,  $\epsilon$ , and the normal component of velocity are specified. The velocity is calculated according to a power law profile, i.e.,  $U(z)/U_r = (z/z_r)^n$ , where  $U(z)$  is the velocity in the direction normal to the upwind boundary,  $U_r$  is a reference velocity,  $Z_r$  is a reference height, and  $n$  is equal to 0.25; tangential components of the velocity are Zero. Here, the reference velocity  $U_r$  is the wind speed measured at a nearby location (at CMU), whose

height is approximately 30m. Profiles for  $\epsilon$  and at the upwind boundary are derived from the velocity profile (Patterson and Appelt, 1989). At the downwind boundary (exit), normal gradients of all flow variables except pressure are set to zero.

In previous research by Etyemezian et al. (1999), the shape of the Cathedral of Learning was approximated by a 30 m x 30 m x 160 m rectangular block (L x W x H). We have been trying to build more realistic physical model of the Cathedral by adding small blocks and prisms to the main body. Some difficulties have been encountered and need to be overcome. A more complicated geometry results in higher number of nodes for the structured mesh, a less streamlined configuration, and thus bigger computational domain. These factors imply more computational time and resources. In addition, we cannot use the symmetric characteristic to reduce the computation time by half, because in most cases, the geometry is not symmetric with respect to the center plane. We are attempting to improve the mesh techniques and reduce the convergence time.

After the airflow field is determined, the multiphase application of FLUENT can be used to calculate trajectories of individual raindrops, which are released above the model geometry and subjected to the computed flow field. The fate of each drop, i.e. whether it impacts on a surface of the building or the ground, can be recorded. Then, combined with measurements of rain intensity, wind speed, and wind direction obtained at CMU, the trajectories can be used for estimation of the total rain delivery to surfaces of the building.

## **2.2 Wind Tunnel Tests**

The CMU wind tunnel has been prepared for testing airflow patterns around a physical model of the Cathedral. Because of the relatively small size of the wind tunnel as well as the simple physical model of the Cathedral, it is difficult to do extensive tests for the entire airflow profile around the building. However, wind tunnel tests can serve very well as a tool for verifying the results from computer modeling of airflow patterns. Hot wire anemometers will be used to quantify the airflow patterns at several points in the wind

tunnel, e.g., close to the windward face, in the near wake, in the far wake, and above the roof.

A literature search on wind tunnel testing of airflow around buildings has provided information on operating parameters and the influence of size reduction on accuracy of the wind tunnel tests.

According to Hansen (1975), for sufficiently high Reynolds numbers ( $>20000$ ), the flow around the model will be independent of the Reynolds number. Thus the flow around the model will be a reasonable approximation to the flow around the Cathedral even though the Reynolds number at the Cathedral is much greater. We will use a small model with a height of about 20 cm. Note that the Cathedral is roughly 160 m high, so there is a size reduction of about 1:1000 for the model.

### **2.3 Field Experiments**

The preparation for on-site measurements of local airflow patterns at the Cathedral has started in summer 1999. Using three Gill Propeller Anemometers, we are setting up to measure wind speeds in the U, V, and W directions at certain points near the building. It is unrealistic to do measurements at many locations, but our need for information on airflow patterns near the walls can be satisfied by on-site measurements at limited number of carefully selected positions. The measured data can then be compared with results of the FLUENT modeling.

We are currently running two experiments: measurement of rain fluxes and collection of meteorological data, which will be covered in detail. The measured wind directions are used in FLUENT to determine the incidence angle of the wind relative to the upwind face of the building. Wind speed data collected at CMU are used to calculate the inflow boundary velocity profile for the modeling domain. Rainfall data are combined with an exponential raindrop size distribution model to derive the numbers and sizes of raindrops impinging on the building walls. Then, by applying raindrop trajectories calculated by FLUENT, rain fluxes can be computed at different locations on the building.

The measured rain fluxes at the Cathedral will be used to examine the correlation between rain washing and soiling at different positions on the building. We will also compare measured data with the calculated rain fluxes from FLUENT modeling.

### **3. Field Experiments**

In this section we describe measurement of horizontal rain fluxes at the Cathedral, and collection of meteorological data at CMU.

#### **3.1 Measurement of Horizontal Rain Fluxes**

PVC sheets with rainwater collection gutters and polyethylene bottles have been set up at 12 locations on the 5<sup>th</sup> floor and 4 locations on the 16<sup>th</sup> floor. Attached to vertical exterior walls, these sheets are designed such that raindrops striking them will drip down the sheet and be collected in a gutter at the bottom.. The gutter then drains into the collection bottle. Figure 3.1 shows a picture of the apparatus. The measurement locations are illustrated in Figure 3.2. We intend to investigate the influence of direction and elevation on wind-driven rain delivery. Due to a lack of terraces, there is no apparatus installed on Bellefield side. Figure 3.3 shows pictures for each measurement location. The soiling patterns on the background range from completely white to heavily soiled. Higher rain fluxes are expected at locations free of soiling.

Ideally, we want to collect the data as soon as possible after a rain event, because evaporation can reduce the amount of water in the bottles. The data are usually collected within 12 hours following a rainstorm.

#### **3.2 Collection of Meteorological Data**

A cup anemometer (014A, Met One Instruments), wind vane (024A, Met One Instruments), and tipping bucket rain gauge (370, Micromet) have been set up on the roof

of Warner Hall on the CMU campus. Figure 3.4 is a picture of the weather station. The wind speed and wind direction measured here are used as an indicator of wind conditions impinging on the Cathedral of Learning. The distance between these two buildings is approximately 0.8 kilometers, which should ensure that the wind conditions measured reflect the actual winds approaching the Cathedral but without the influence of the Cathedral itself.

A datalogger (CR21X, Campbell Scientific) has been used to record average wind speed and wind direction over a 15-minute interval and total amount of rainfall in that period. Eight-bin frequency count for wind direction ( $45^\circ$  per bin), maximum instantaneous wind speed during each interval, and the wind direction at the time of maximum wind speed are also recorded. Two different types of vector average wind speeds are calculated: an arithmetic vector average and a weighted vector average. A program was coded and imported into the datalogger for data retrieval and manipulation. The program functions by taking readings from the three instruments every 15 seconds. These readings are subsequently stored in RAM. Every 15 minutes, the datalogger extracts the readings from the RAM and processes them.

At the end of every 15-minute interval, the datalogger exports a set of data to a storage module, which has capacity for up to one month of data. Currently, we switch the storage module every week.

### **3.3 Maintenance of Equipment**

The equipment at the Cathedral site and at the Warner Hall site requires a good deal of maintenance. As both sites are exposed to the outdoor environment, equipment is replaced or repaired frequently. Originally we used 1-liter bottles for the rain flux experiment. However, due to large rainfall events that took place at the beginning of the summer it was necessary to replace the bottles with larger ones. This required reinstalling the mounting brackets and replacing the 1-liter bottles with 2-liter bottles. The bottles have not overflowed since they were replaced.

The Warner Hall site also had some minor problems, most of which involved routine maintenance, such as tightening screws on the tripods, and checking if the rain gauge is level.

## **4. Results of Field Experiments**

After several months of preparation and testing, field experiments were started in July 1999 for collection of meteorological data and direct measurement of horizontal rain fluxes. This section will present all data collected through the end of September 1999.

### **4.1 Meteorological Data**

From 7/24/99-9/30/99, the data show that measurable rainfall occurred in a total of 184 15-minute intervals. The total rainfall during this period was 221 mm. All data for those intervals are presented in Table 4.1.

### **4.2 Horizontal Rain Flux Data**

In the 10 week period 7/24/99 - 9/30/99, 13 data sets were obtained, which are shown in Table 4.2. Each data set corresponds to one rainfall episode. Here, one rainfall episode refers to all rainfall during the time between two measurements. The data sets for brief rainfall episodes ending on 7/24/99, 8/5/99, 8/27/99 and 9/5/99 are not listed because no rain water was collected in any of the bottles. In Table 4.2, each number represents the horizontal rain flux to the PVC sheet at one location during one rainfall episode. For data in July and August, any number equal to or greater than 1000 ml means that the bottle overflowed, so that the true rain flux at that location should be higher than 1000 ml. Starting from 9/1/99, we began using 2000 ml bottles.

## **5. Discussion**

In this section, the meteorological data collected on the roof of Warner Hall are compared with data from NOAA National Data Center to determine the credibility of our measurements. The meteorological data are interpreted in several ways. In addition, the relationship between the meteorological values and horizontal rain fluxes are examined.

### **5.1 Comparison of Meteorological Data**

After setting up the weather station on the roof of Warner Hall, on-site calibrations of the wind speed and wind direction sensors as well as the rain gauge were conducted according to the manual (Met One Instruments, 1994). These procedures should be able to assure the proper operation of the meteorological equipment. Nevertheless, it is important to validate our measurements with results from trusted sources of data.

Surface meteorological data for Pittsburgh were obtained from the NOAA National Data Center (NNDC) web site (NNDC, 1999). There are two sets of data available. One is from Pittsburgh International Airport (Call Sign: PIT, Latitude:  $40^{\circ}30'$ , Longitude:  $-80^{\circ}13'$ ), and another is from Allegheny County Airport (Call Sign: AGC, Latitude:  $40^{\circ}21'$ , Longitude:  $-79^{\circ}56'$ ). PIT is approximately 24 kilometers northwest of our weather station, while AGC is approximately 10 kilometers to the south. Therefore, the spatial differences should be taken into consideration when making the comparisons. Examples of results are presented in Figures 5.1 -5.3. These figures show comparisons of hourly mean wind speed, wind direction, and cumulative rainfall during a 16-day period from 7/16/99 to 7/31/99. Generally, the temporal trends are very similar between our data and the national network data. Most discrepancies can be explained by spatial differences. Based on the comparisons, we conclude that the data collected on the roof of Warner Hall are representative of actual conditions.

## 5.2 Interpretation of Meteorological Data

The cumulative rainfall data from 7/24/99 - 9/30/99 are plotted in Figure 5.4. The vertical distance from one point to the next reflects rainfall in a 15-minute interval. The total rainfall during this 10-week period was 221 mm.. Rainfall on each day varied significantly. Thirty-eight percent of the rainfall over the period was contributed by two large storms on 7/28/99 and 7/29/99. Storms on 8/1/99, 8/24/99 and 9/29/99 accounted for about 10 percent of the overall rainfall. A common characteristic among these storms is that they all have at least one 15-minute interval with very high rainfall. The most extreme example is on 8/24/99, when 15.75 mm rainfall, or 77 percent of a 2-hour storm, occurred in only one 15-minute period. Such strong rainfall can greatly influence the impingement of raindrops on building surfaces.

As discussed in Section 2, the calculation of airflow around the Cathedral is performed at wind incidence angles of  $0^\circ$  and  $45^\circ$ . Therefore, in order to be used as inputs to FLUENT modeling, measured wind directions are placed in one of eight sectors, each spanning  $45^\circ$ . In Table 4.1, the sector numbers 1 to 8 refer to wind directions N, NE, E, SE, S, SW, W, NW respectively.

During each 15-minute interval, wind direction changes a lot. The eight-bin frequency for wind direction data show that in each interval, the wind has come from at least two direction sectors, while in some intervals, the wind has come from all eight direction sectors. The data output by the datalogger are 15-minute mean wind directions, which are calculated from 60 instantaneous readings during the period. The sector for the mean wind direction usually corresponds to, or at least is close to, the direction from which the wind comes most frequently. This correspondence also exists between mean wind direction and the direction sector associated with maximum wind in a 15-minute interval.

Figure 5.5 shows the overall meteorological conditions for 184 rainy intervals during the period 7/24/99 - 9/30/99. On the left is a wind rose graph for this period. The radical scale represents the fraction of time the wind is coming from the direction indicated.

Graphs b and c present the average rainfall intensity and average wind speed associated with each wind direction during the rain events in the period. The most frequent wind directions during rain events were N, NW, and W. The directions are also associated with the highest wind speeds and relatively high rain intensities. Although average rain intensity was the highest during SE winds, this is due to the one severe storm interval on 8/24/99 mentioned above. As shown in Figure 5.6, after we removed that interval, the highest rain intensities occurred when N, NW and W winds were dominant.

These results coincide well with our expectations. Note that the Fifth Avenue and Bigelow Boulevard sides of the Cathedral, facing SW and NW, have much less soiling than the other two sides of the Cathedral. This is consistent with the shorter-term experiments of Etyemezian et al. (1999).

### **5.3 Correlation between Meteorological Data and Rain Flux Data**

Impingement of rain on a building wall is expected to be greatest during intense rainfall, and when winds approach the wall at relatively high speeds. This hypothesis is consistent with data collected in the 10-week period.

Figure 5.7 shows a general positive correlation between total rainfall and total rainwater collected at all 16 locations at the Cathedral during the period 7/24/99 - 9/30/99. Each point in the figure represents one rainfall episode.

The volume of rainwater collected at each location corresponds to the total volume of raindrops impinging on the PVC sheet. By dividing this value by area of the surrogate surface and the total time of rainy periods, we can calculate the rain flux per unit area of the surface (mm/hr).

Figure 5.8 includes 13 graphs, one for each rainfall episode during 7/24/99 - 9/30/99. The diagram in the middle is a simplified top-view of the Cathedral of Learning. Every small pie-chart shows the relative amount of rainwater collected at an individual location. A

completely black pie-chart represents the highest rain flux value for that episode. The large circle overlying the Cathedral outline provides the base for presenting the meteorological data. Each straight line going toward the center represents one 15-minute interval. The mean wind direction for this interval can be read from the x-axis, while the rain intensity is represented by length of the line. The length between two gridlines refers to 1.016 mm rainfall. At the upper right corner, additional information is listed.

From these graphs, we can find the relationship between rain fluxes and meteorological conditions near the Cathedral. For example, consider the graph of August 13-16, the winds were mainly coming from N, NW and W during 10 rainfall intervals. As a result, bottles on the Fifth Ave side which faces NW received higher amounts of rain. The Bigelow Blvd side did not receive high rain fluxes because the rain intensities were much lower for the intervals with W winds. In contrast, the rainfall episode on August 24-25 had a very different profile. The dominant wind directions were E and SE. A high intensity rainfall interval occurred when wind was SE, towards the Forbes Ave side. All PVC sheets on this side received large amounts of rain, while those on the Fifth Ave side had much lower rain fluxes. Another finding is that the bottles on 16th floor normally receive higher rain fluxes than the bottles facing the same direction on the 5th floor. This has been repeated between locations 13, 14 and locations 6, 7 on the Fifth Ave side, as well as between locations 15, 16 and locations 11, 12 on the Forbes Ave side. This is consistent with the results from the previous modeling of raindrop impingement (Etyemezian et al., 1999). Building surfaces at higher elevations are exposed to higher winds and more rain than surfaces at lower levels.

Data from these experiments have provided strong evidence that high horizontal rain fluxes are the result of favorable wind direction, high wind speeds and intense rainfall.

## 6. Future Work

In the fourth year of the project, we will continue the quantification of surrounding airflow patterns and rain delivery to the walls of the Cathedral of Learning. Both on-site measurements of airflow around the Cathedral and wind tunnel tests using a small scale physical model of the building will be conducted to obtain verification of the results from FLUENT modeling. We are planning work in several areas:

To improve simulation of airflow around the Cathedral, we will use a more realistic geometry of the Cathedral in FLUENT modeling. Airflow patterns under different wind conditions will be calculated. Meteorological data collected on Warner Hall will be used as inputs.

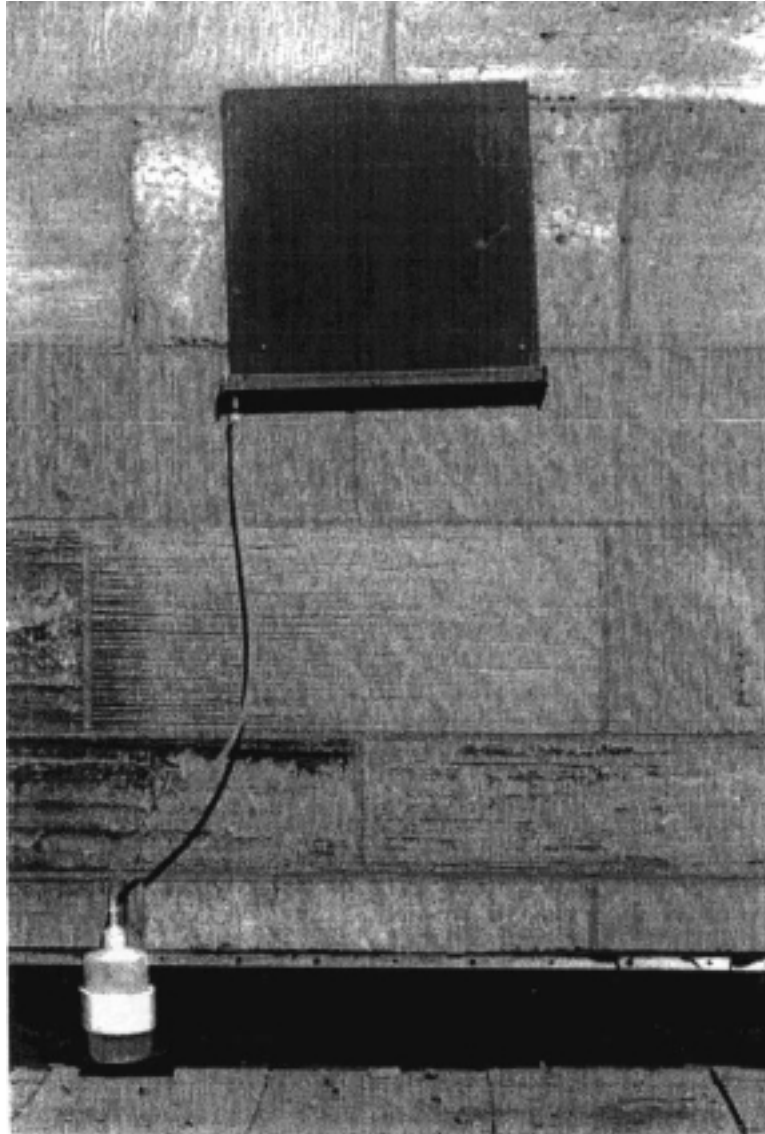
Once airflow patterns around the Cathedral are calculated, the multiphase modeling application of FLUENT will be used for simulating raindrop impingement. The trajectories of individual raindrops will be calculated numerically with reference to the computed airflow field; the fate of the raindrops will be recorded. Combining raindrop trajectories with raindrop size distributions from the literature and rainfall data, we will be able to calculate the rain fluxes to the building walls.

The CMU wind tunnel will be used for testing airflow patterns around a physical model of the Cathedral. We will use a small model with a height of about 20 cm. Hot wire anemometers will be used to quantify the airflow patterns at several points in the wind tunnel. The results will enable verification of the computer modeling.

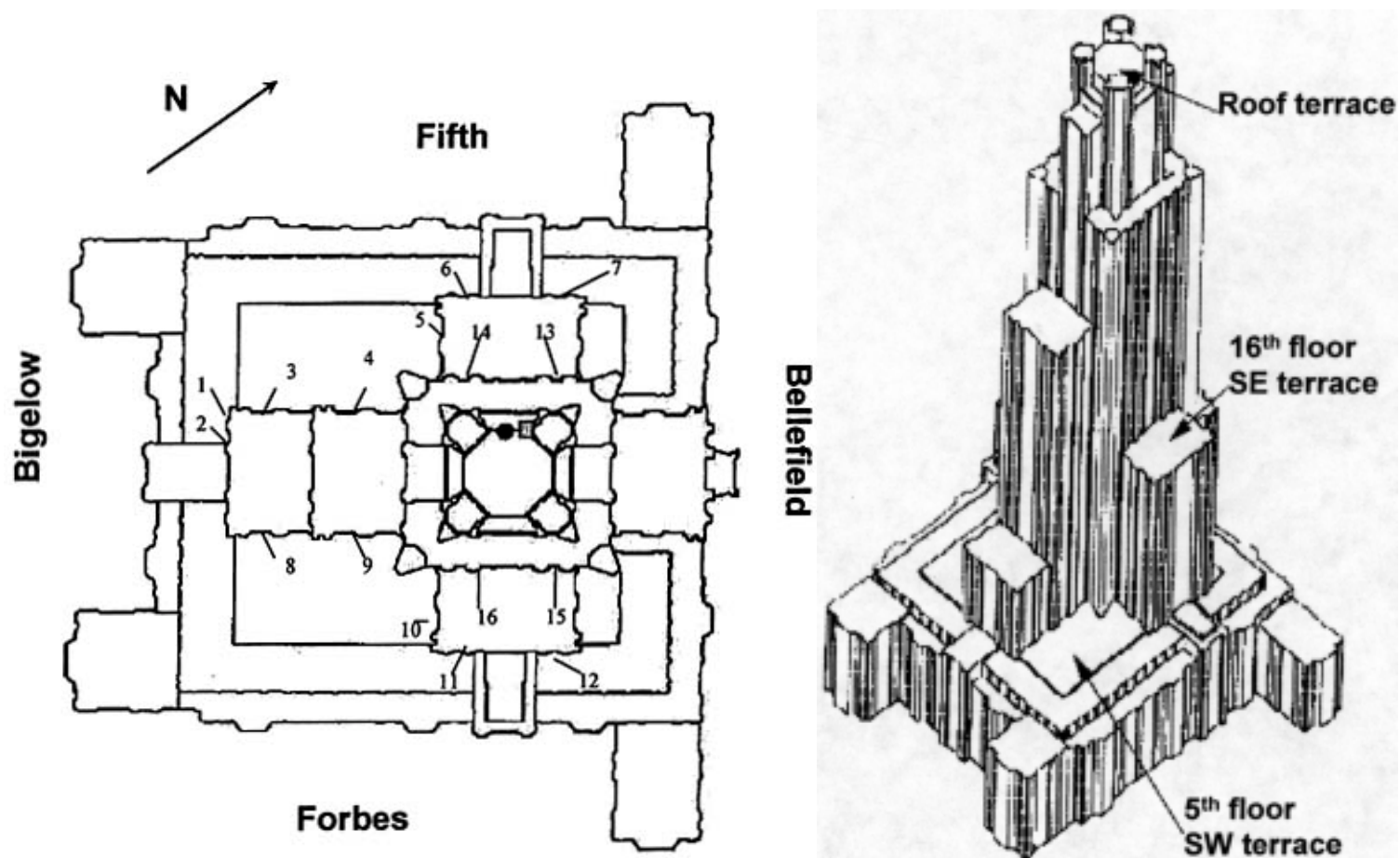
We will also conduct field work, measuring wind speeds in the U, V, and W directions at several points near the Cathedral walls. The field data will be compared with the results from FLUENT modeling to improve the modeling efforts. We will collect continuous meteorological data for a full year, including rain intensity, wind speed, and wind direction on the roof of Warner Hall. In addition, we will collect continuous data on horizontal rain fluxes at 16 locations on the 5th and 16th floor of the Cathedral.

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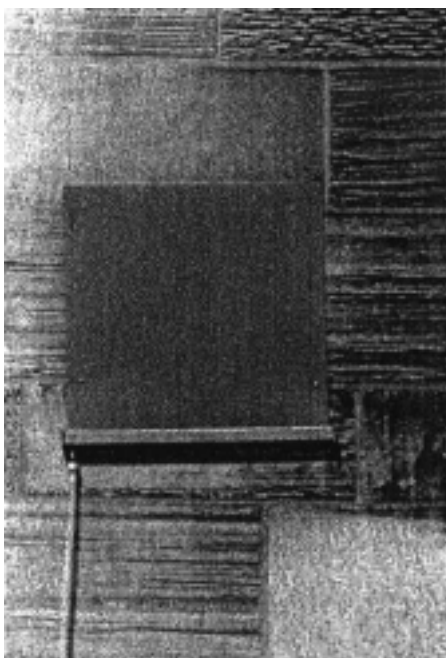


**Figure 3.1 Experimental apparatus for measuring rain fluxes**

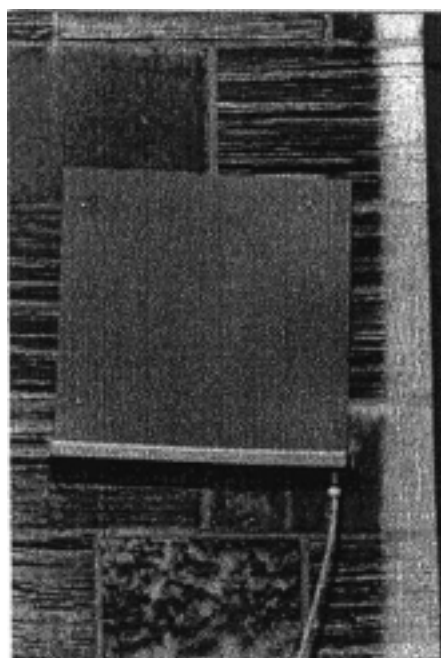


**Figure 3.2 Rain flux measurement locations on the Cathedral.**  
 Locations 1-12 are on the 5<sup>th</sup> floor. Locations 13-16 are on the 16<sup>th</sup> floor.

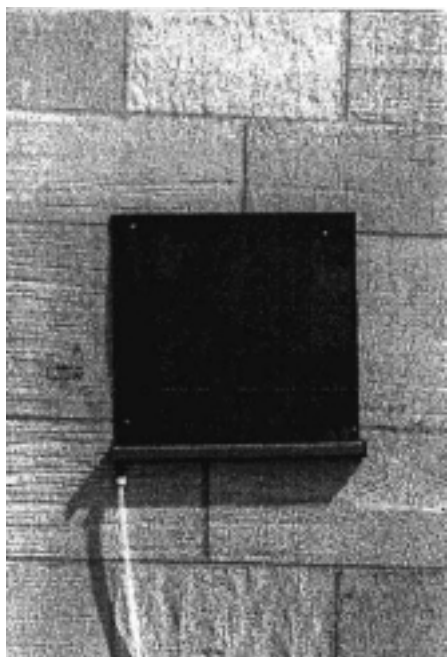
## Fifth floor



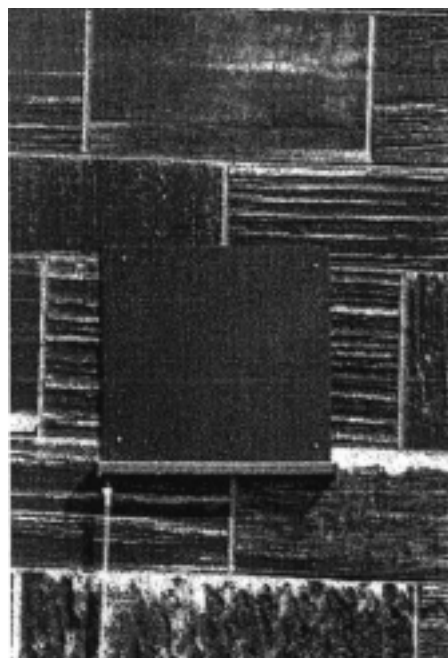
Location #1



Location #2



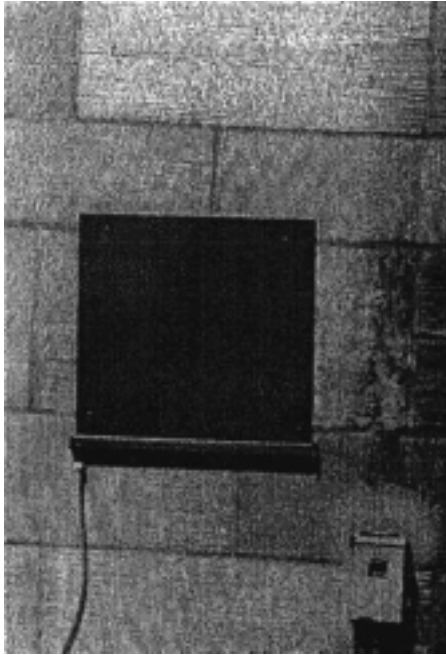
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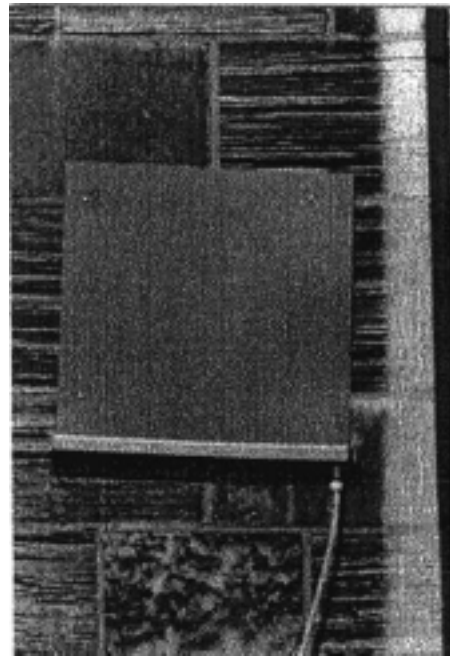
Location #4

**Figure 3.3 Different soiling patterns at each location**

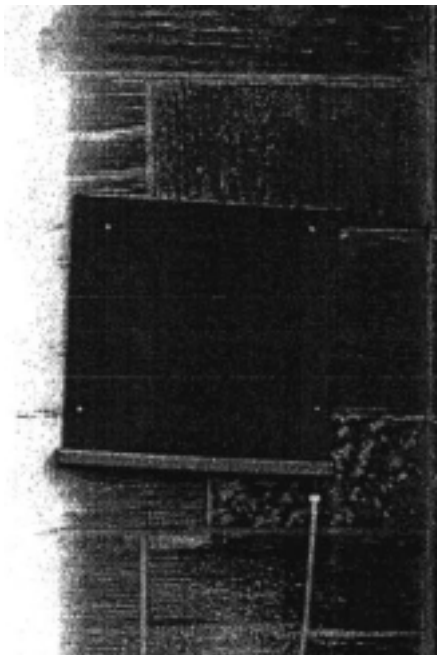
## Fifth floor



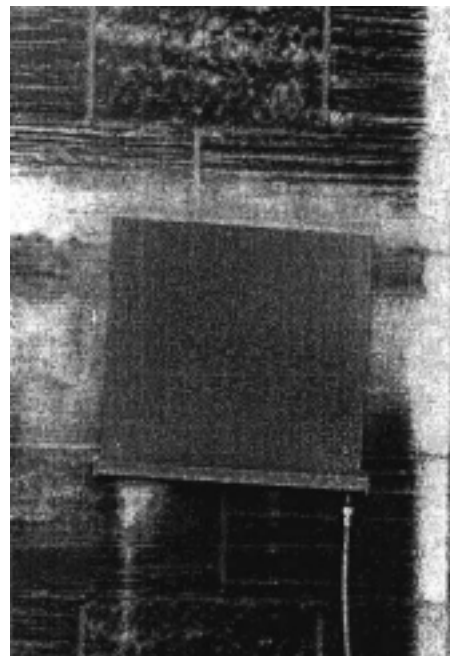
Location #5



Location #6



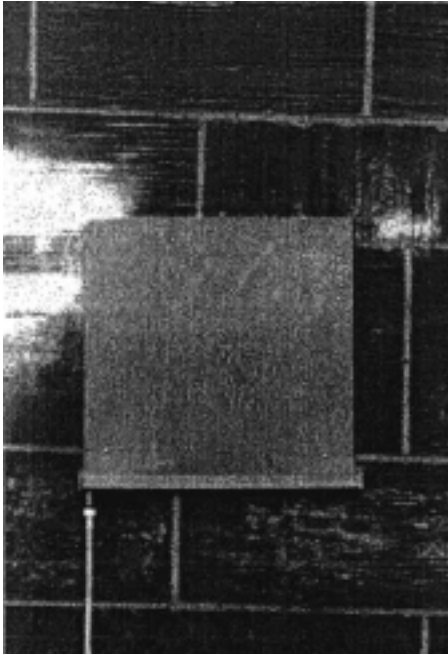
Location #7



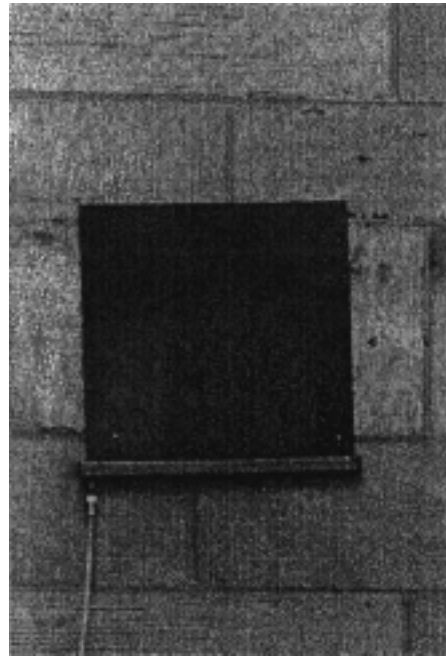
Location #8

**Figure 3.3 Different soiling patterns at each location**

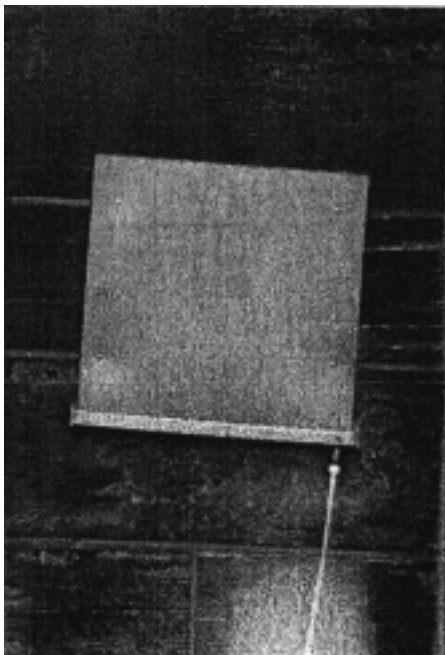
## Fifth floor



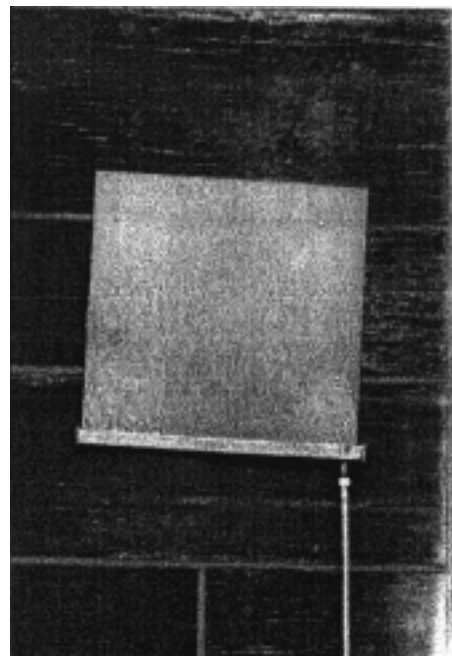
Location #9



Location #10



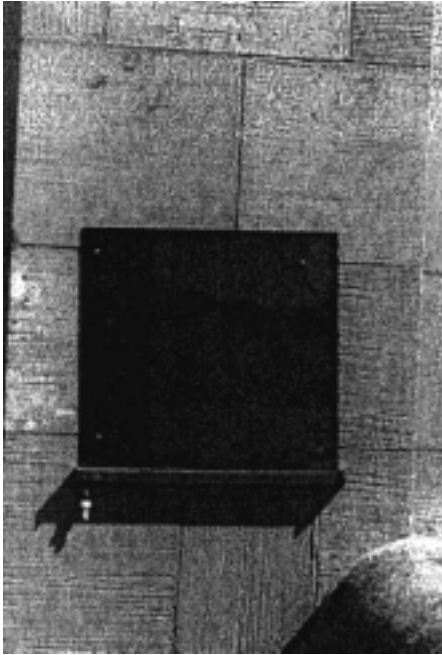
Location #11



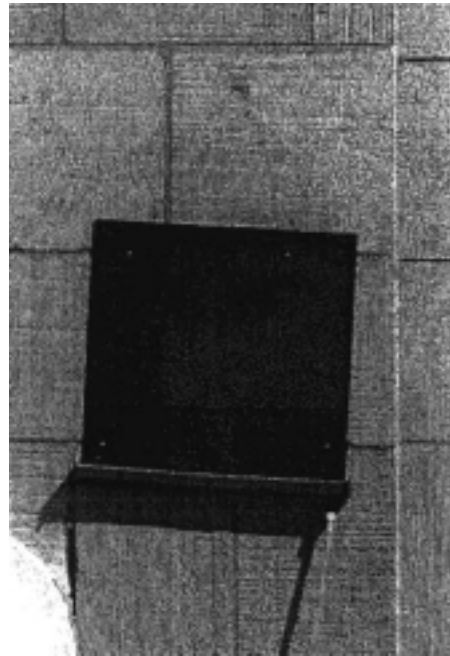
Location #12

**Figure 3.3 Different soiling patterns at each location**

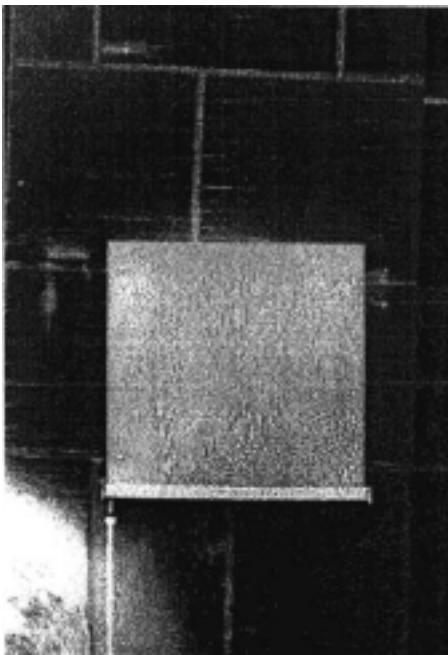
## Fifth floor



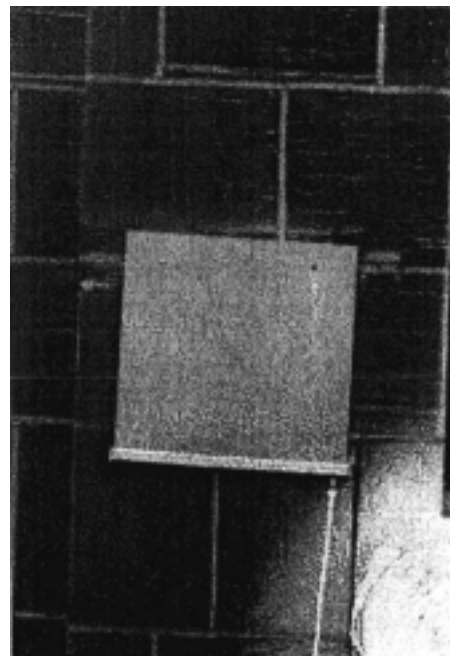
Location #13



Location #14

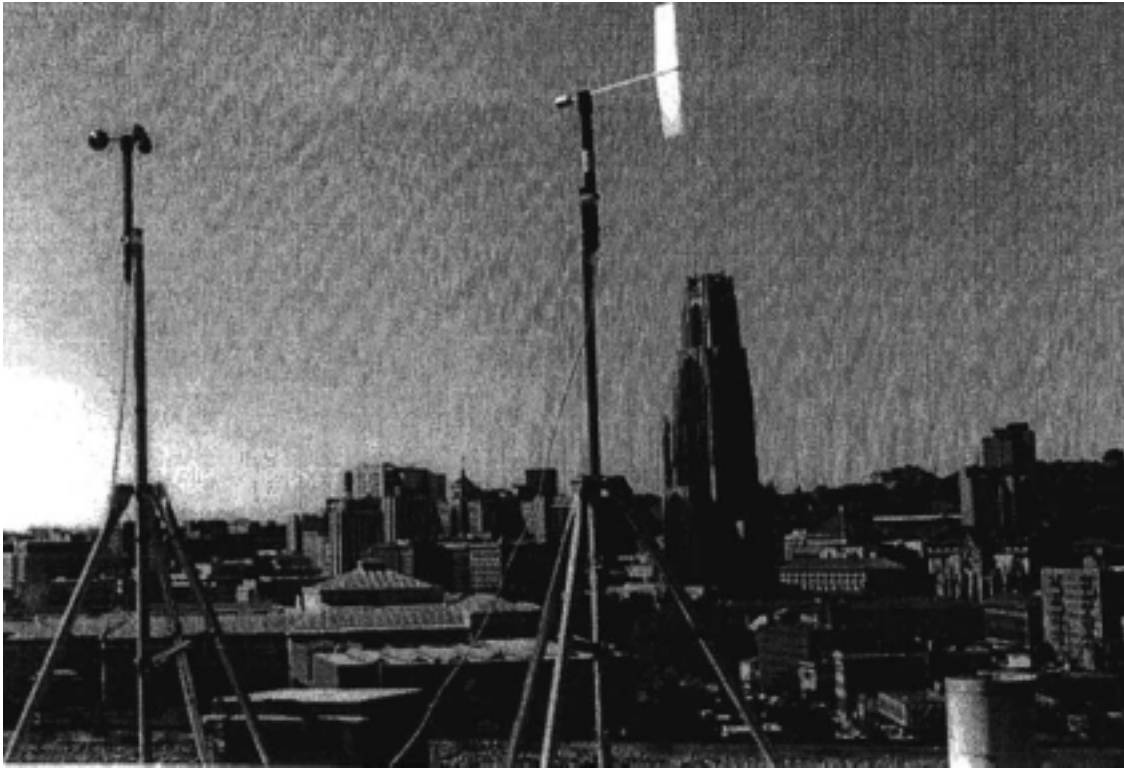


Location #15



Location #16

**Figure 3.3 Different soiling patterns at each location**



**Figure 3.4 Weather station on the roof of Warner Hall at CMU**

From left to right: wind speed sensor, wind direction sensor, and tipping bucket rain gauge. The Cathedral of Learning is in the background at a distance of approximately 0.8 km.

Figure 5.1 Comparison of wind direction data during 7/16/99 - 7/31/99

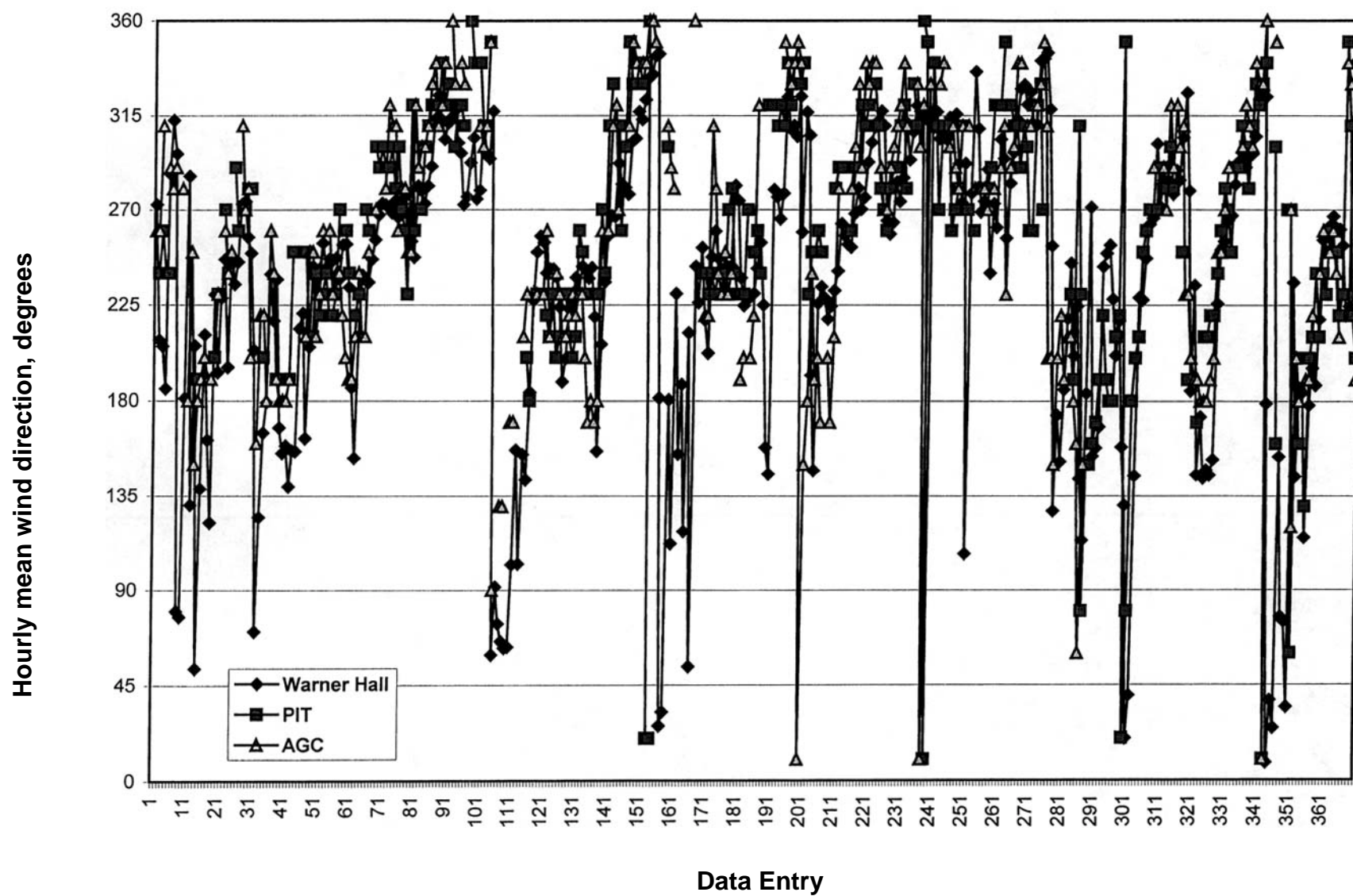
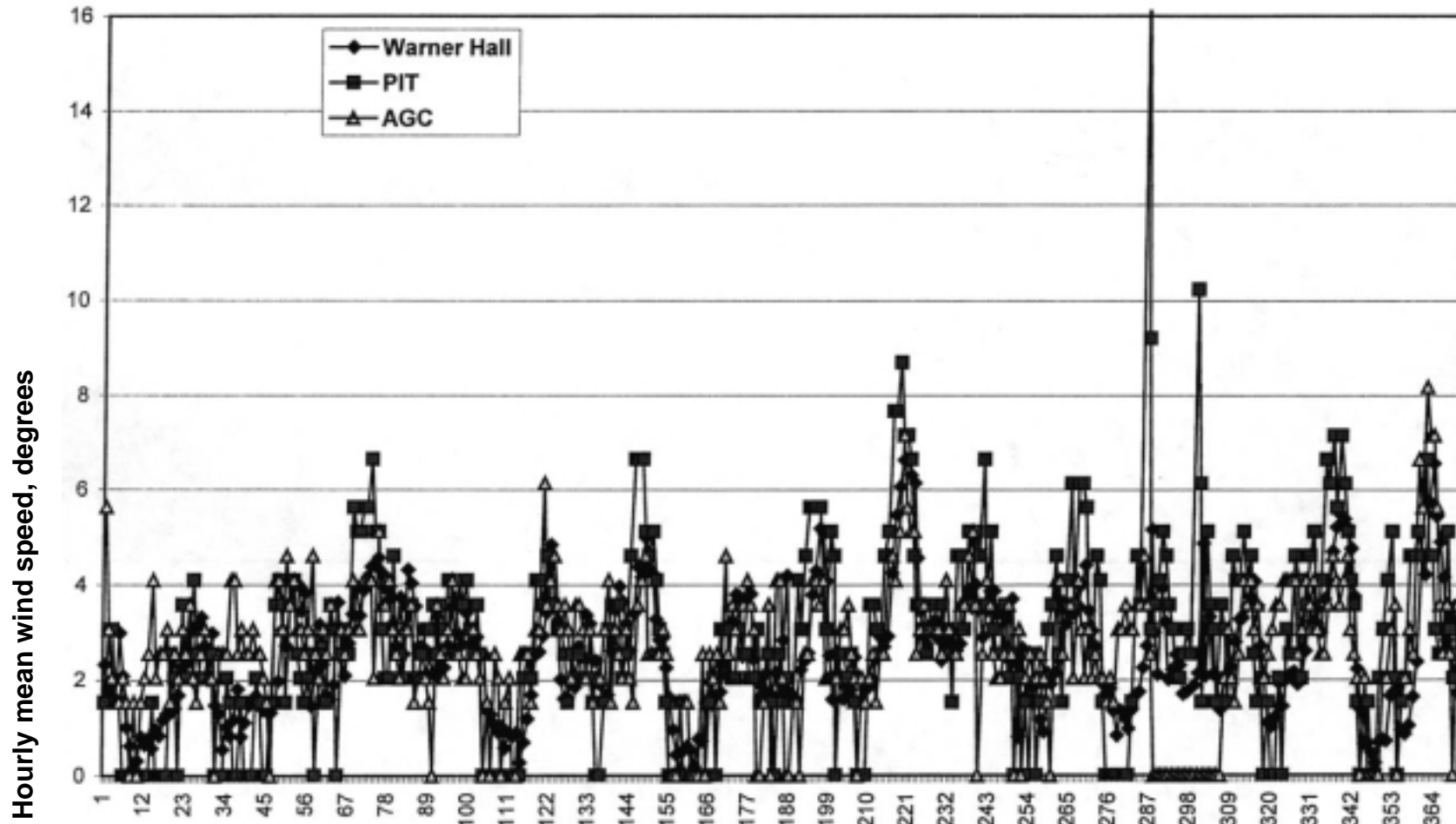
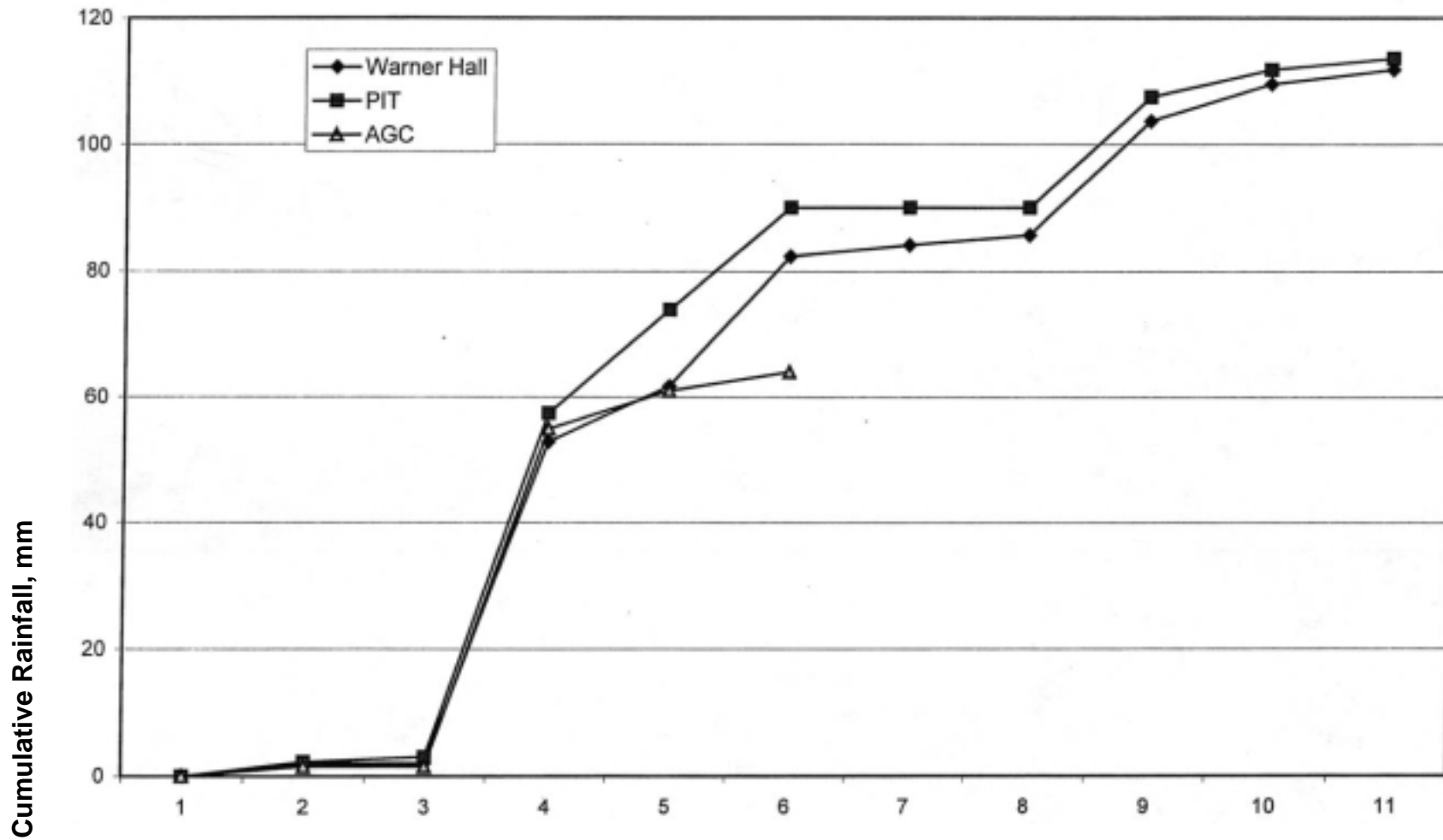


Figure 5.2 Comparison of wind speed data during 7/16/99 -7/31/99



Note: For PIT and AGC, all data less than 3 knots/hour (1.53 m/s) are set to 0.

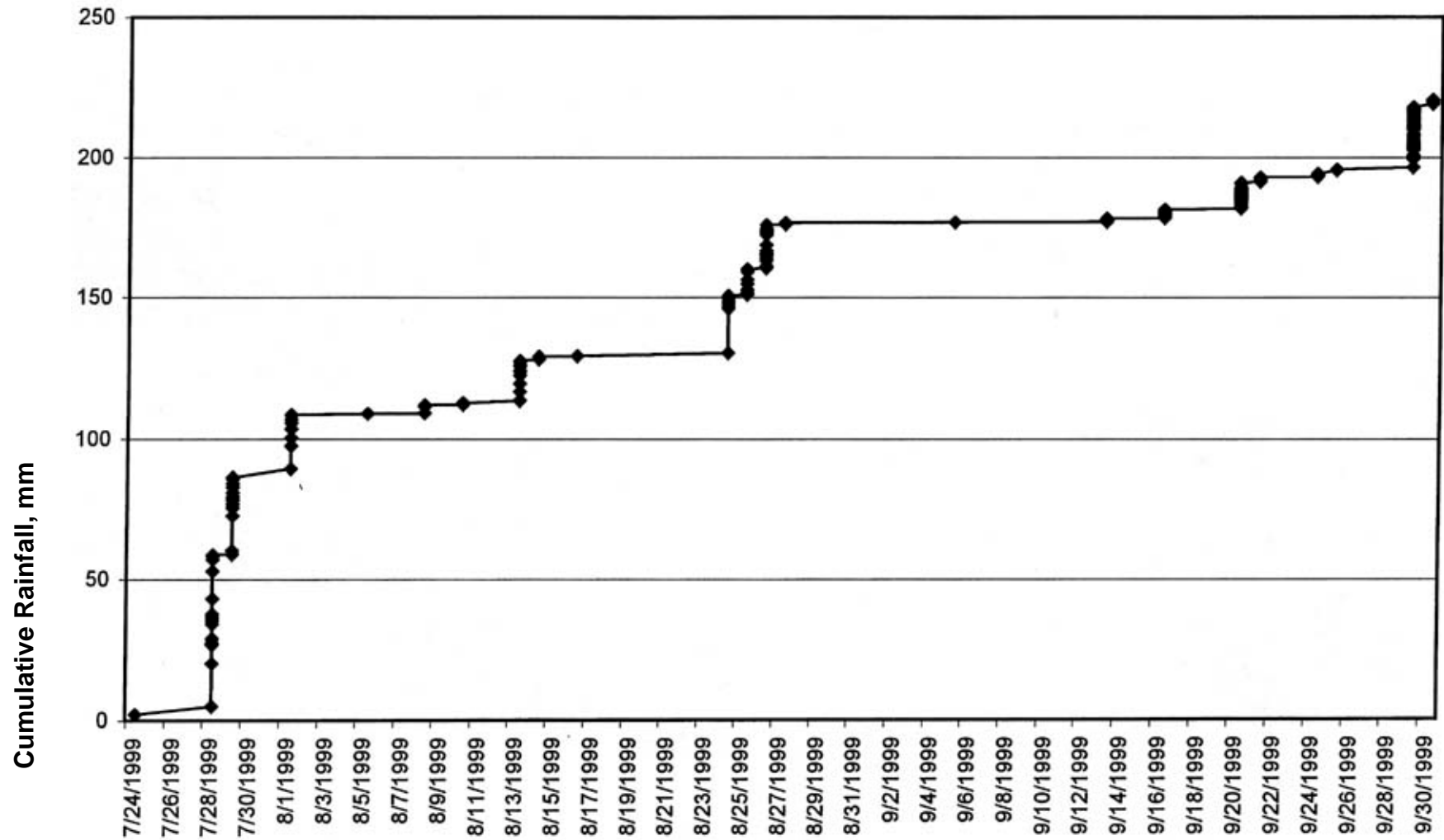
**Figure 5.3 Comparison of cumulative rainfall during 7/16/99 - 7/31/99**

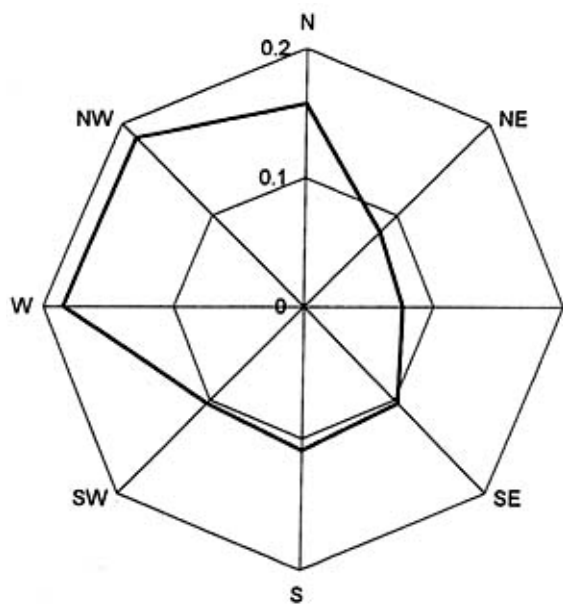


**Data Entry**

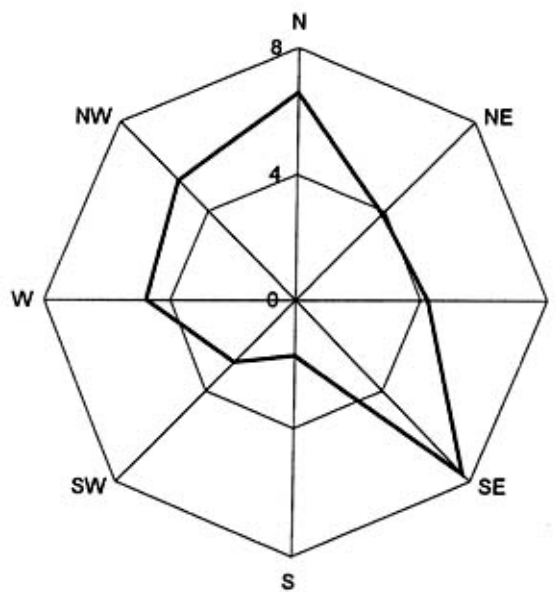
**Note: The weather station at Allegheny County Airport (AGC) was down during the rain event on 07/28/99.**

Figure 5.4 Cumulative rainfall for the period 7/24/99 - 9/30/99

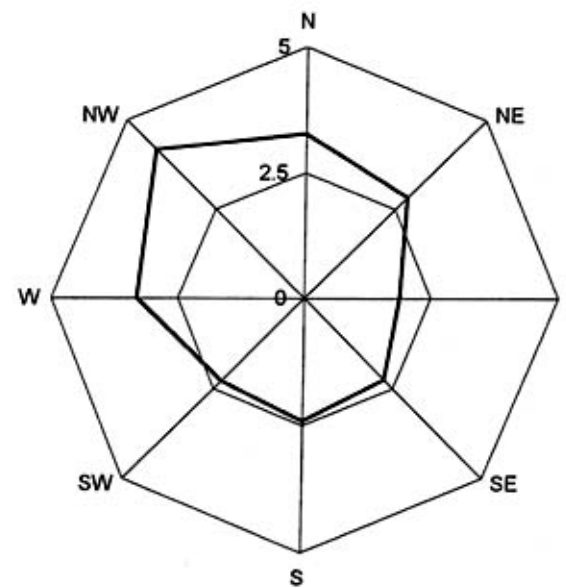




Wind direction frequency

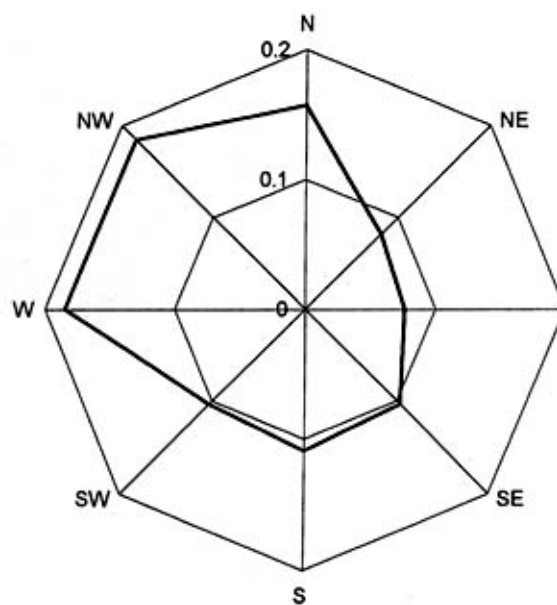


Mean rain intensity (mm/hr)

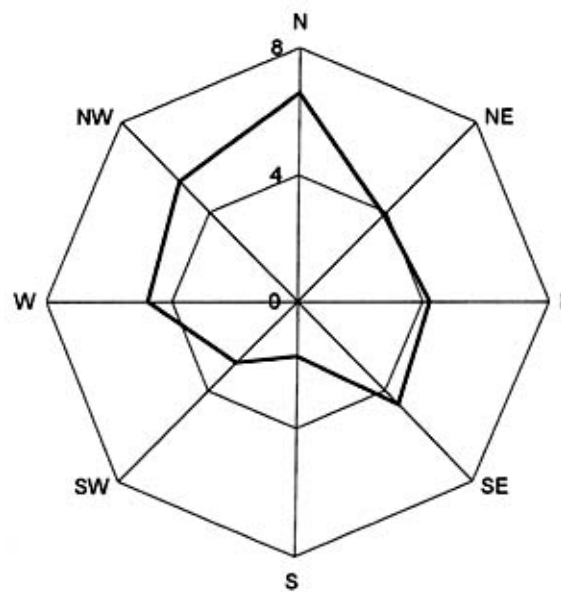


Mean wind speed (m/s)

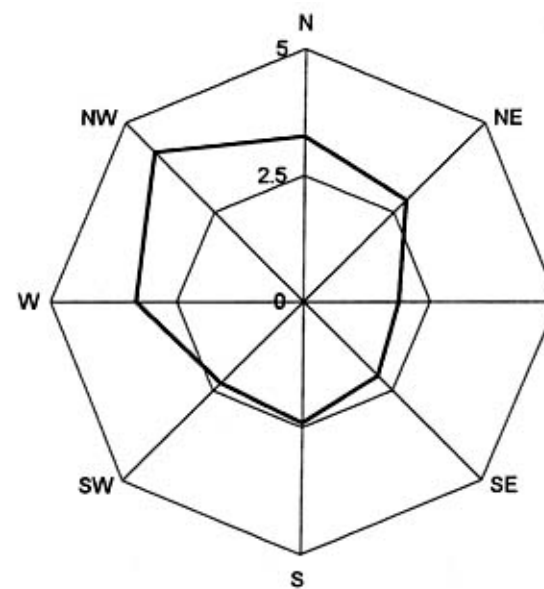
**Figure 5.5 Meteorological conditions during rainy periods for 7/24/99 - 9/30/99**



Wind direction frequency



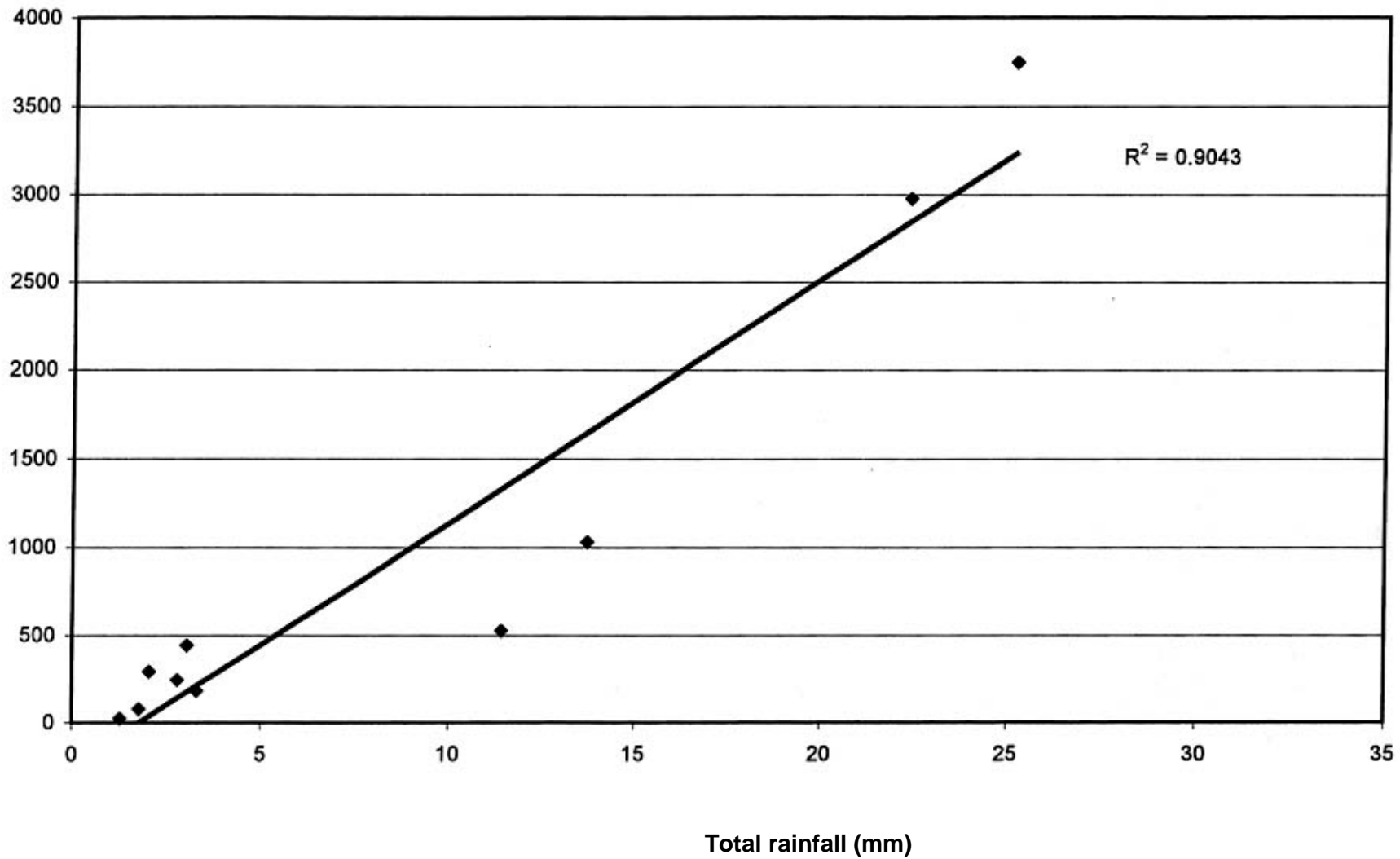
Mean rain intensity (mm/hr)



Mean wind speed (m/s)

**Figure 5.6 Meteorological conditions during rainy periods for 7/24/99 - 9/30/99  
(without one severe storm interval on 8/24/99)**

Figure 5.7 Total rain water collected vs. total rainfall



Note: Data used in this figure do not include 3 rainfall episodes when collection bottles overflowed.

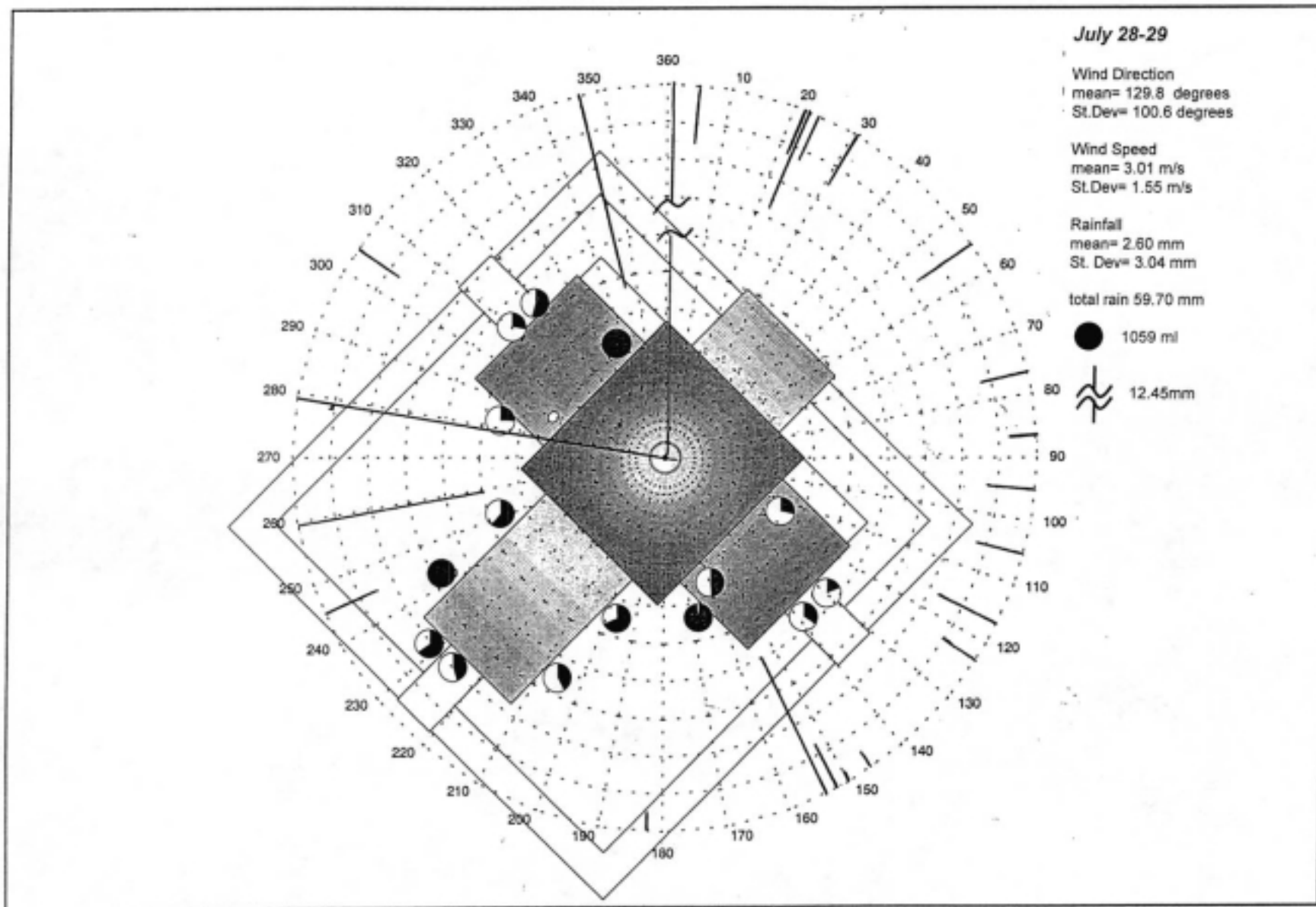


Figure 5.8 Correlation between meteorological data and rain flux data (episode #2)

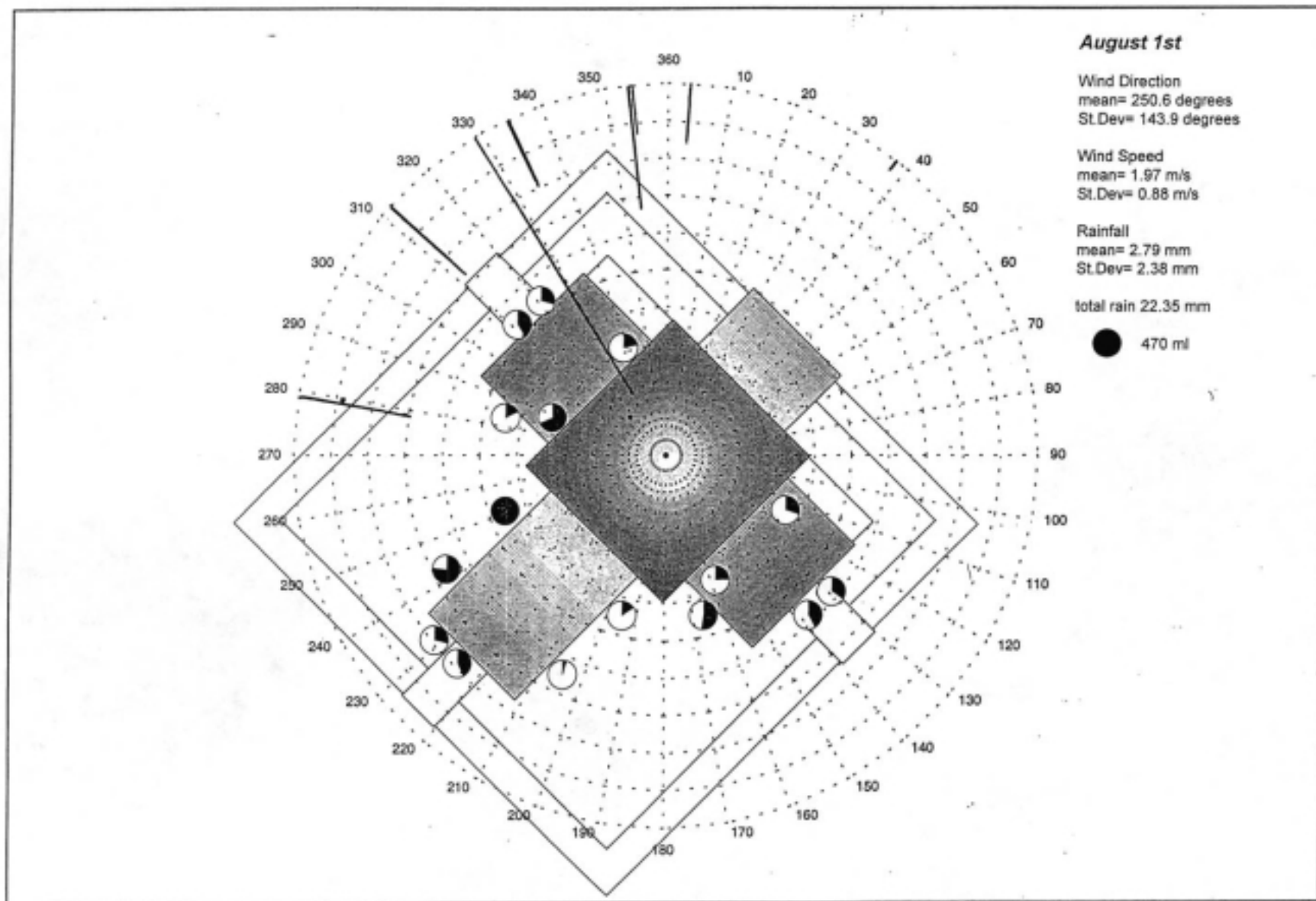


Figure 5.8 Correlation between meteorological data and rain flux data (episode #3)

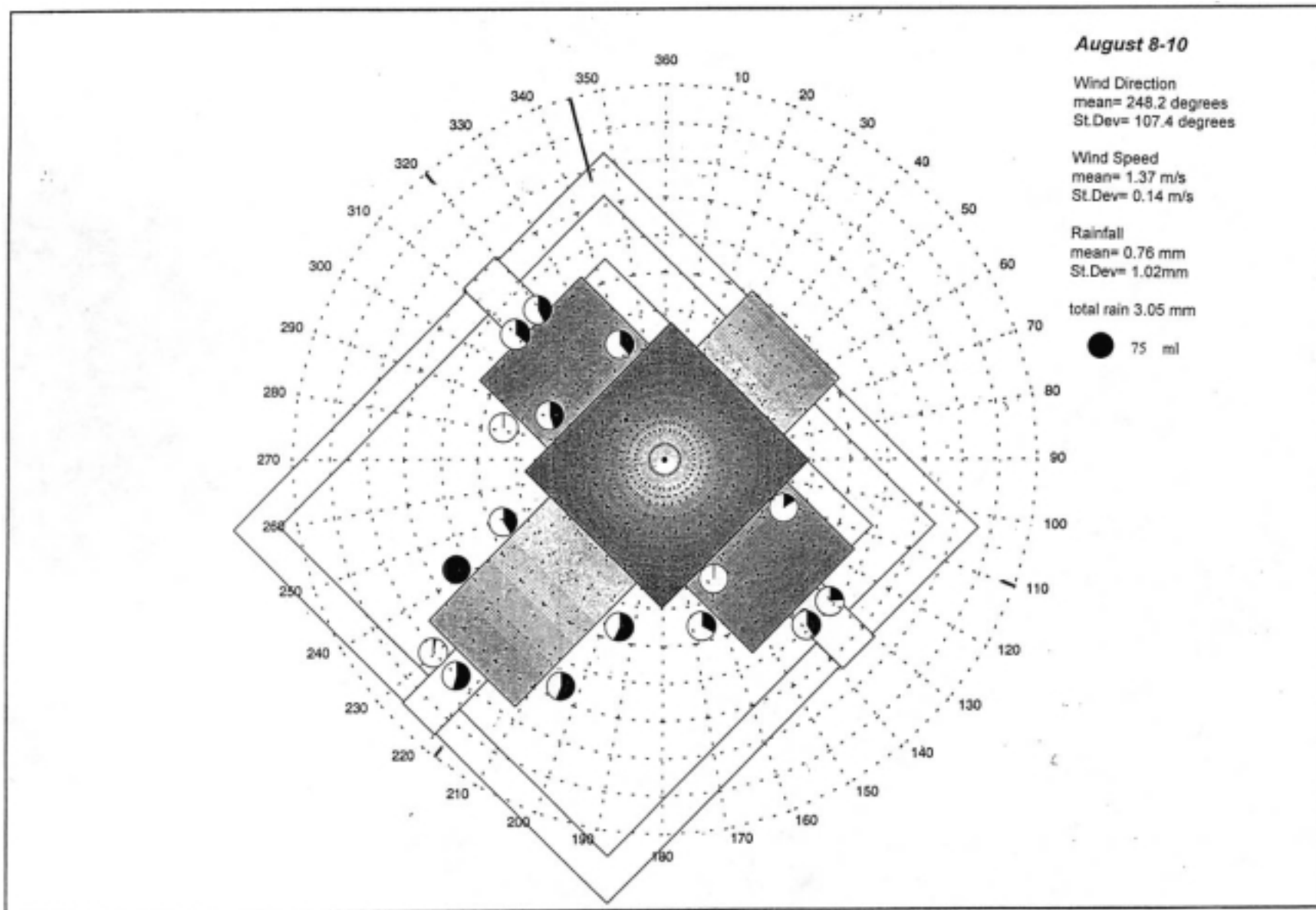


Figure 5.8 Correlation between meteorological data and rain flux data (episode #5)

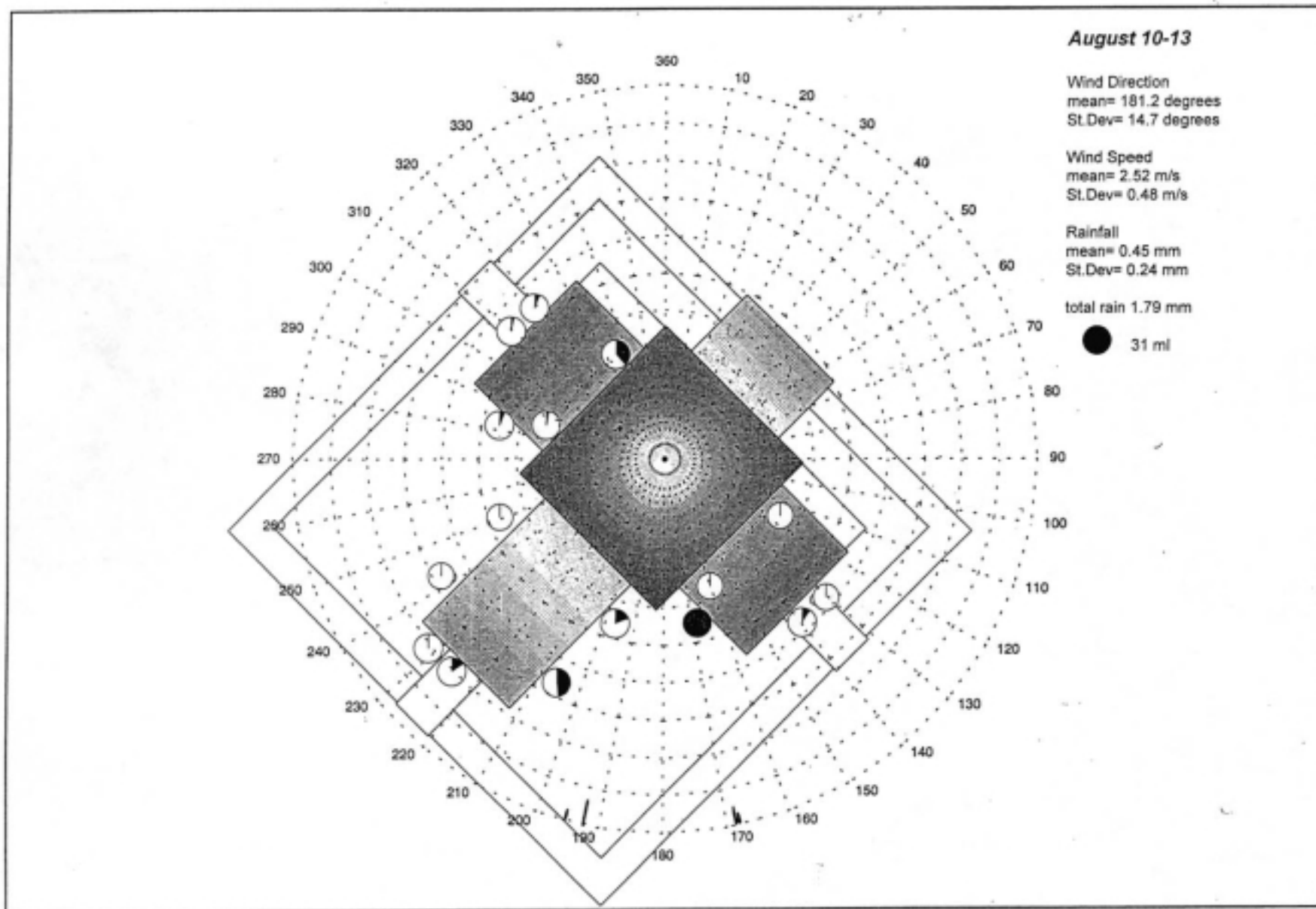
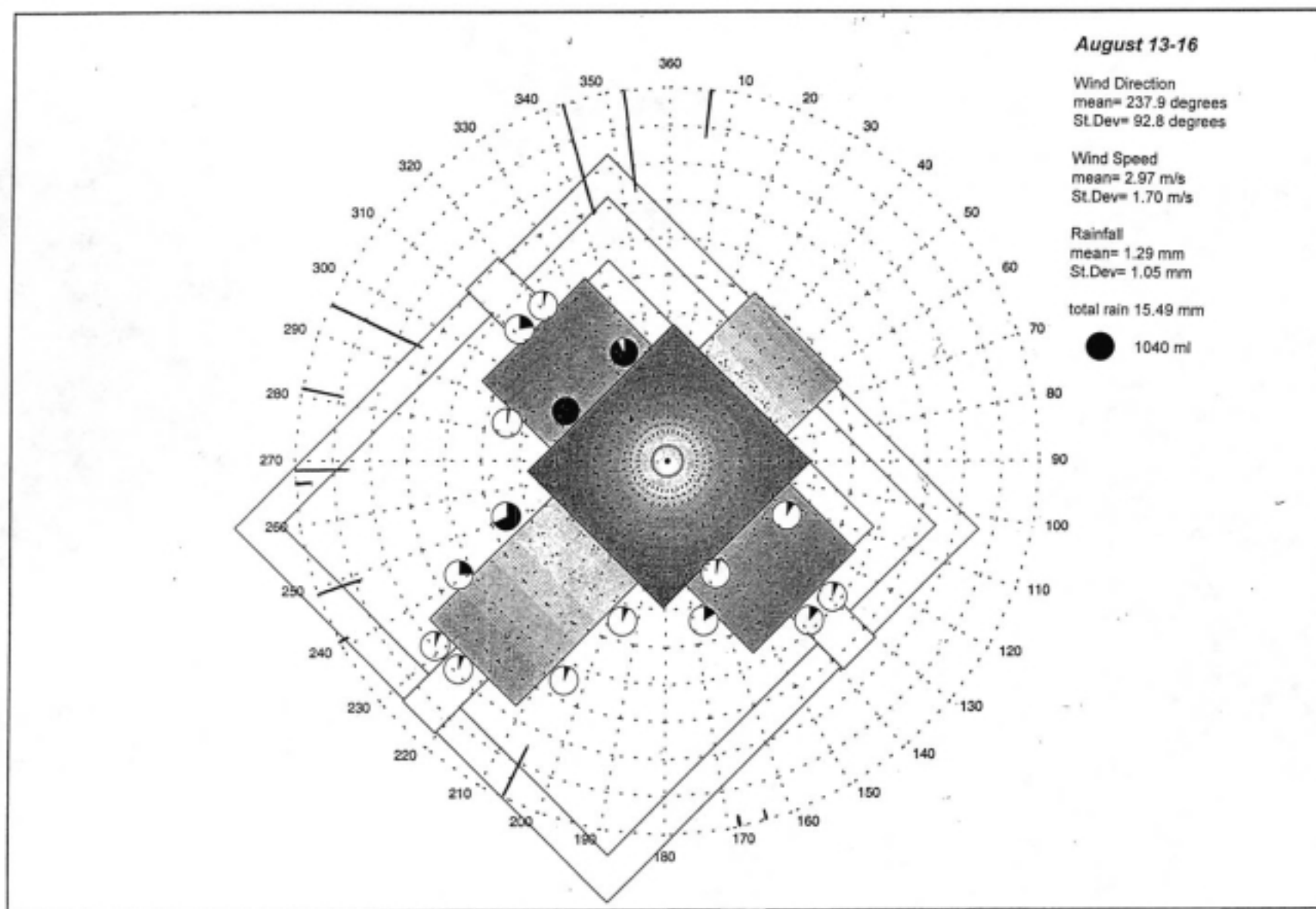


Figure 5.8 Correlation between meteorological data and rain flux data (episode #6)



**Figure 5.8 Correlation between meteorological data and rain flux data (episode #7)**

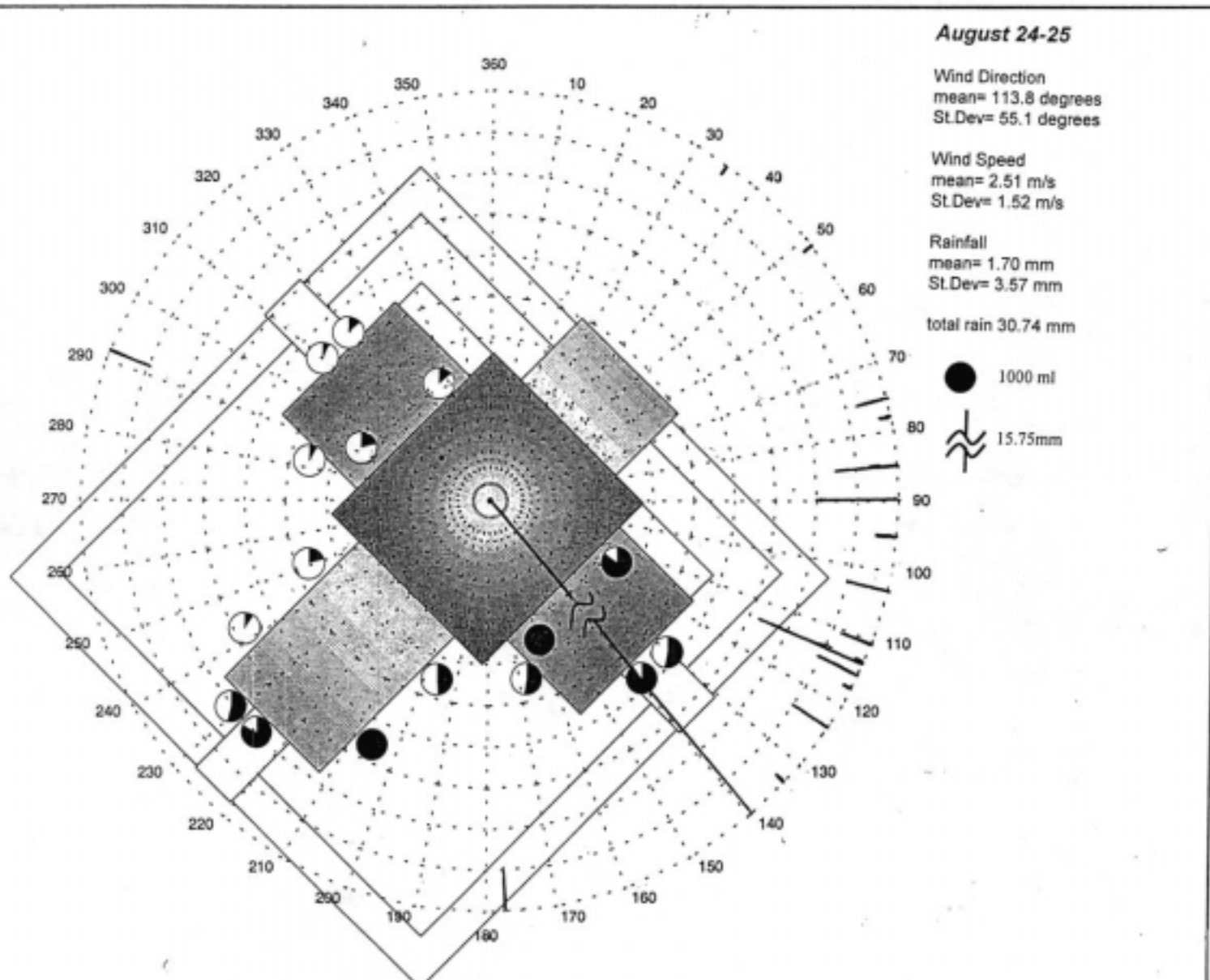


Figure 5.8 Correlation between meteorological data and rain flux data (episode#8)

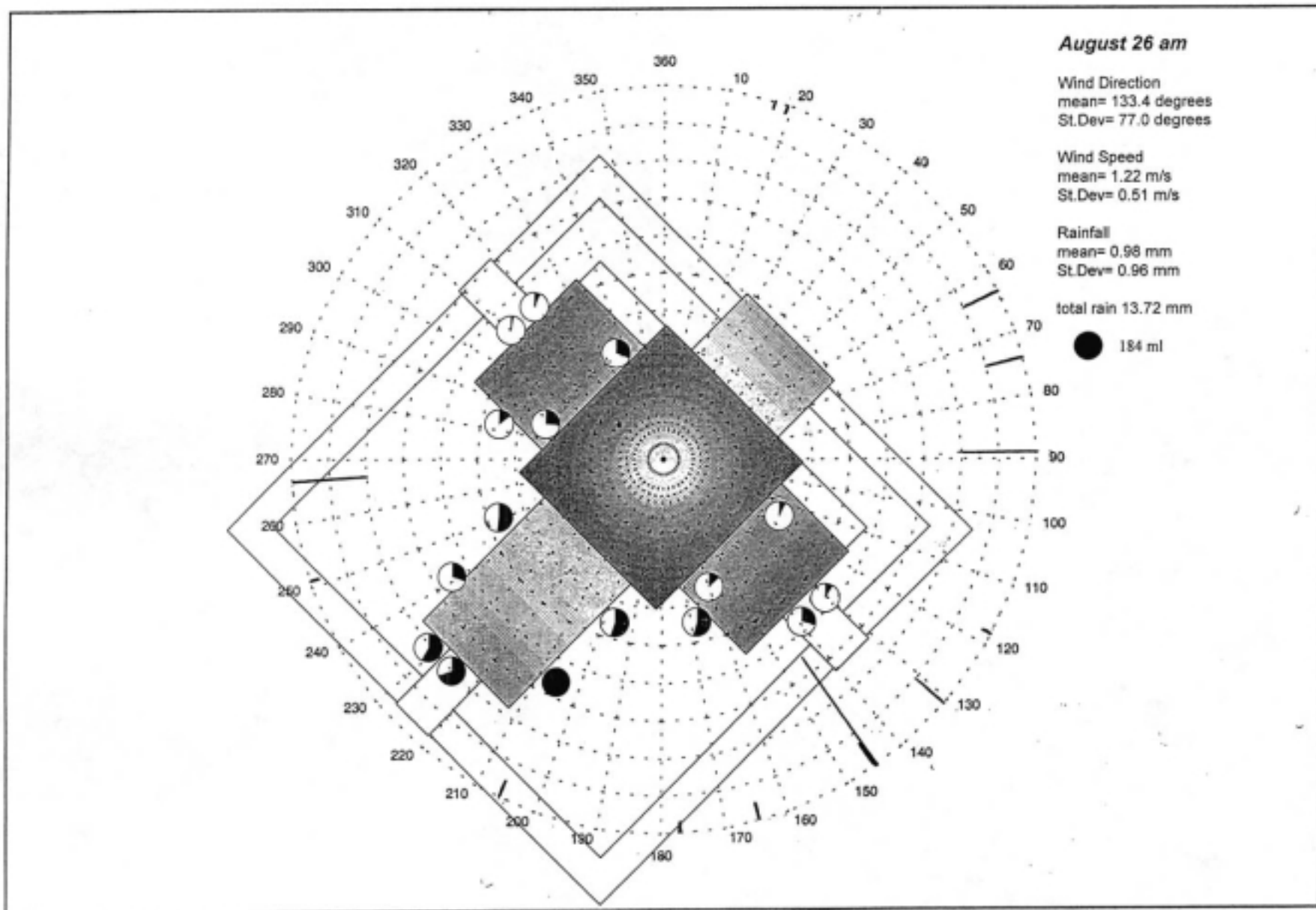
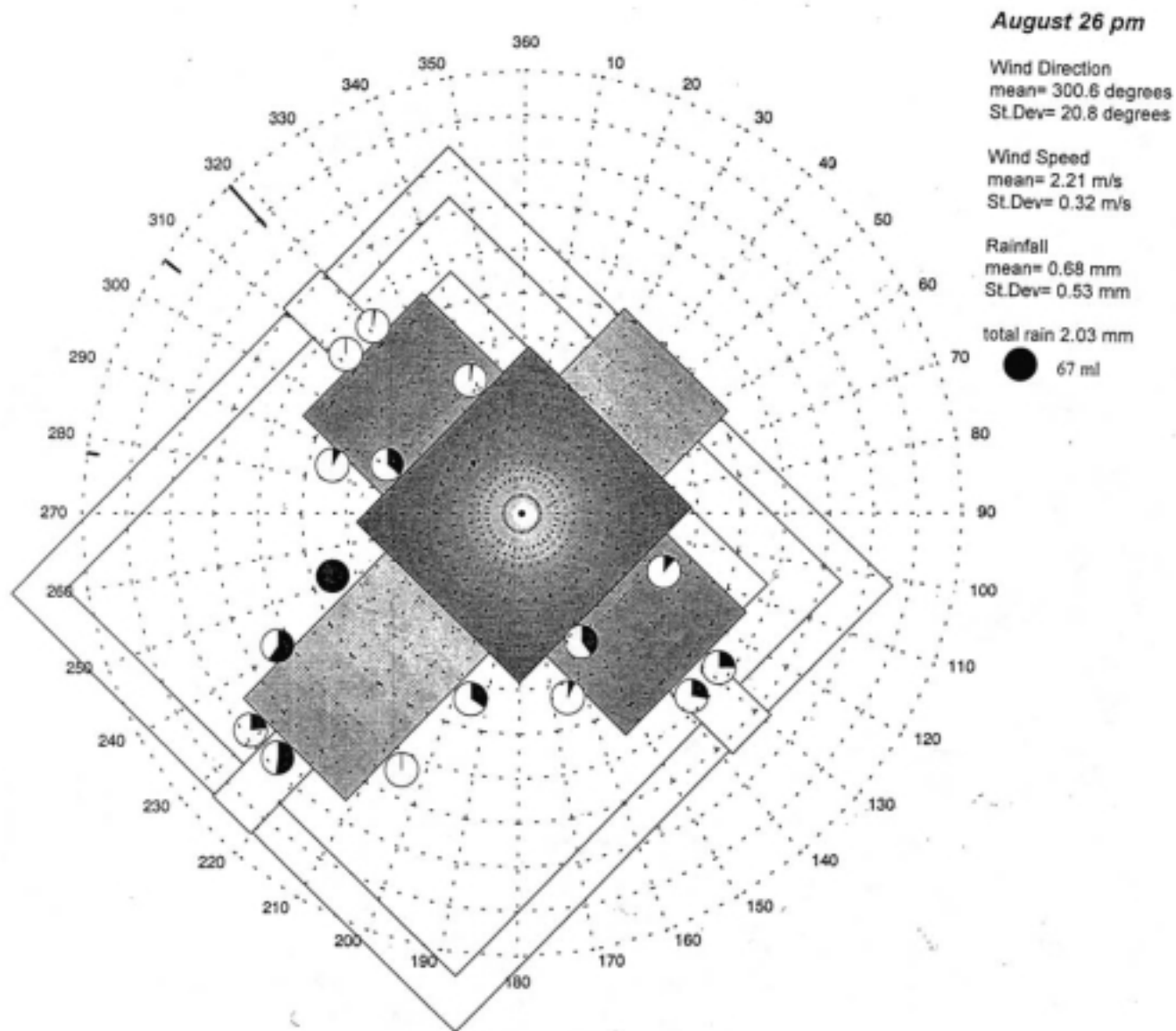


Figure 5.8 Correlation between meteorological data and rain flux data (episode#9)



**Figure 5.8 Correlation between meteorological data and rain flux data (episode #10)**

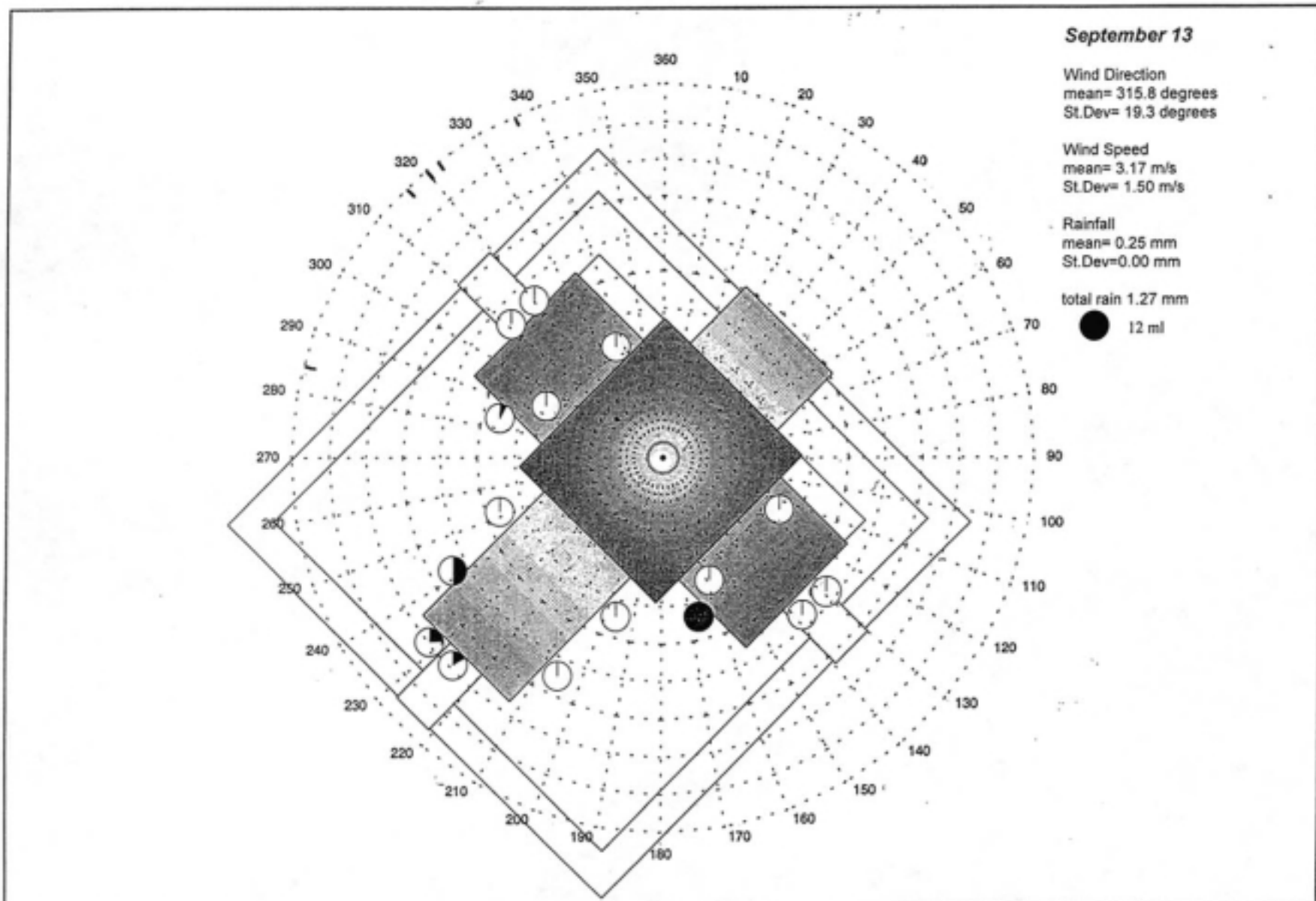
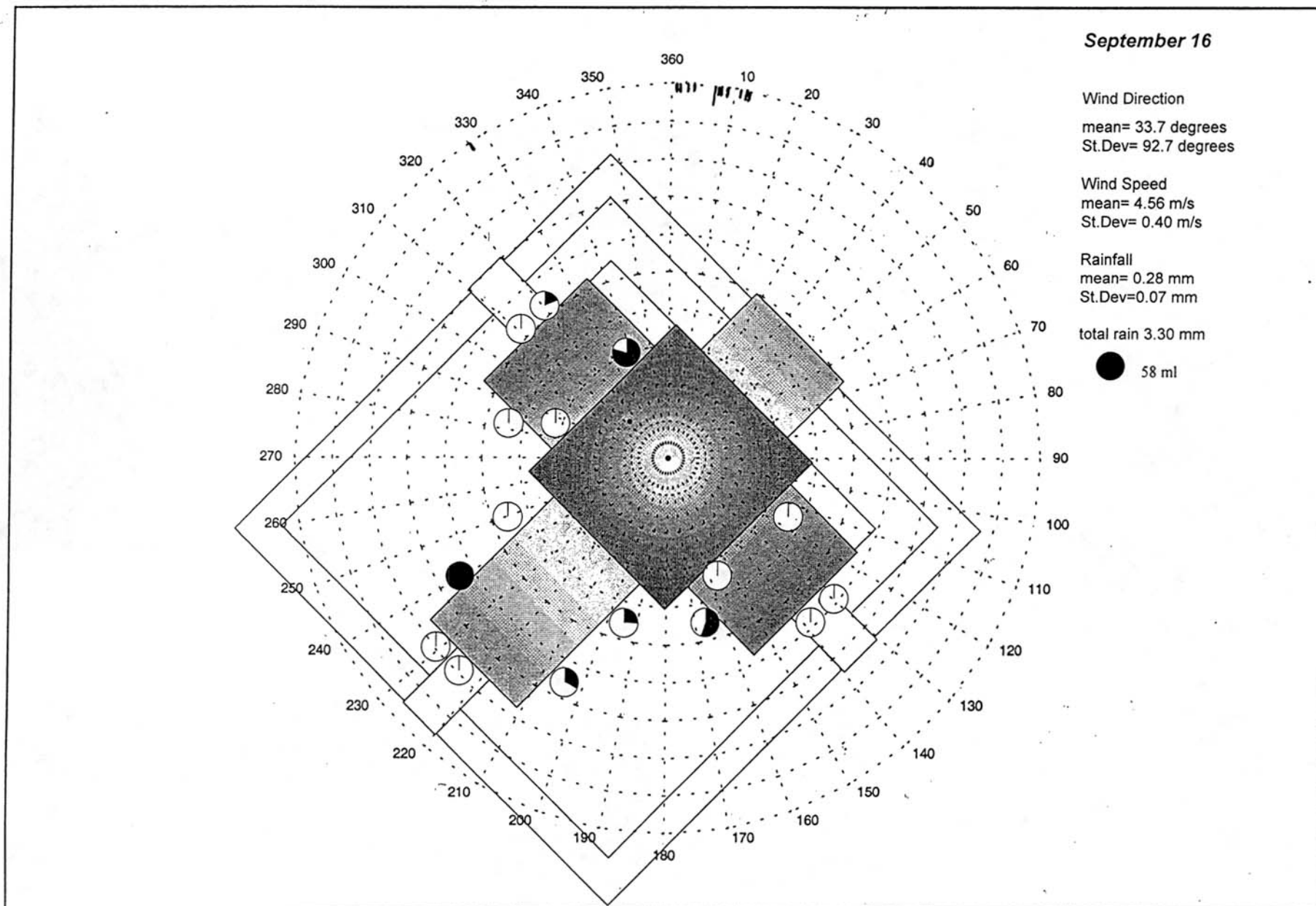


Figure 5.8 Correlation between meteorological data and rain flux data (episode #13)



**Figure 5.8 Correlation between meteorological data and rain flux data (episode #14)**

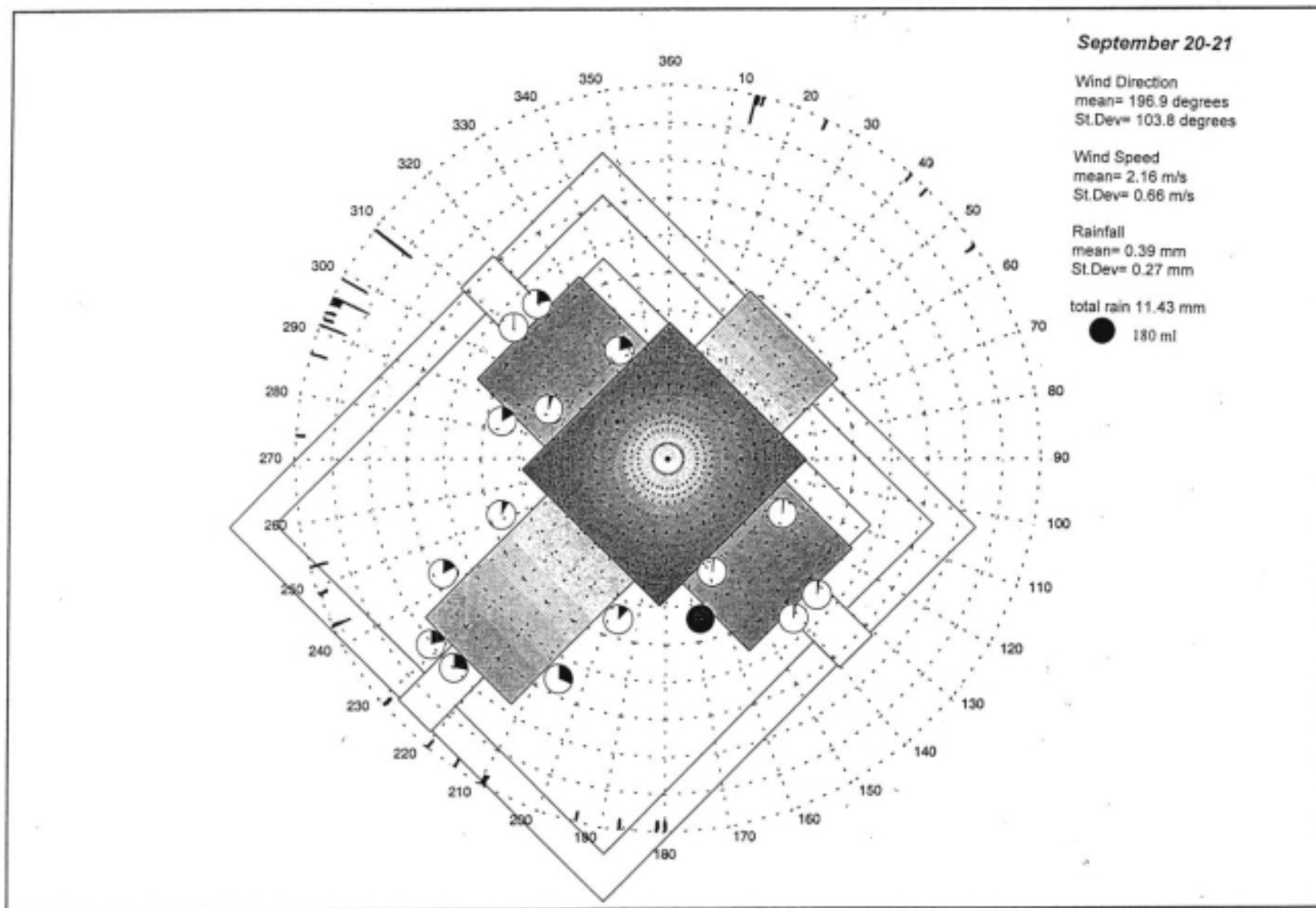


Figure 5.8 Correlation between meteorological data and rain flux data (episode #15)

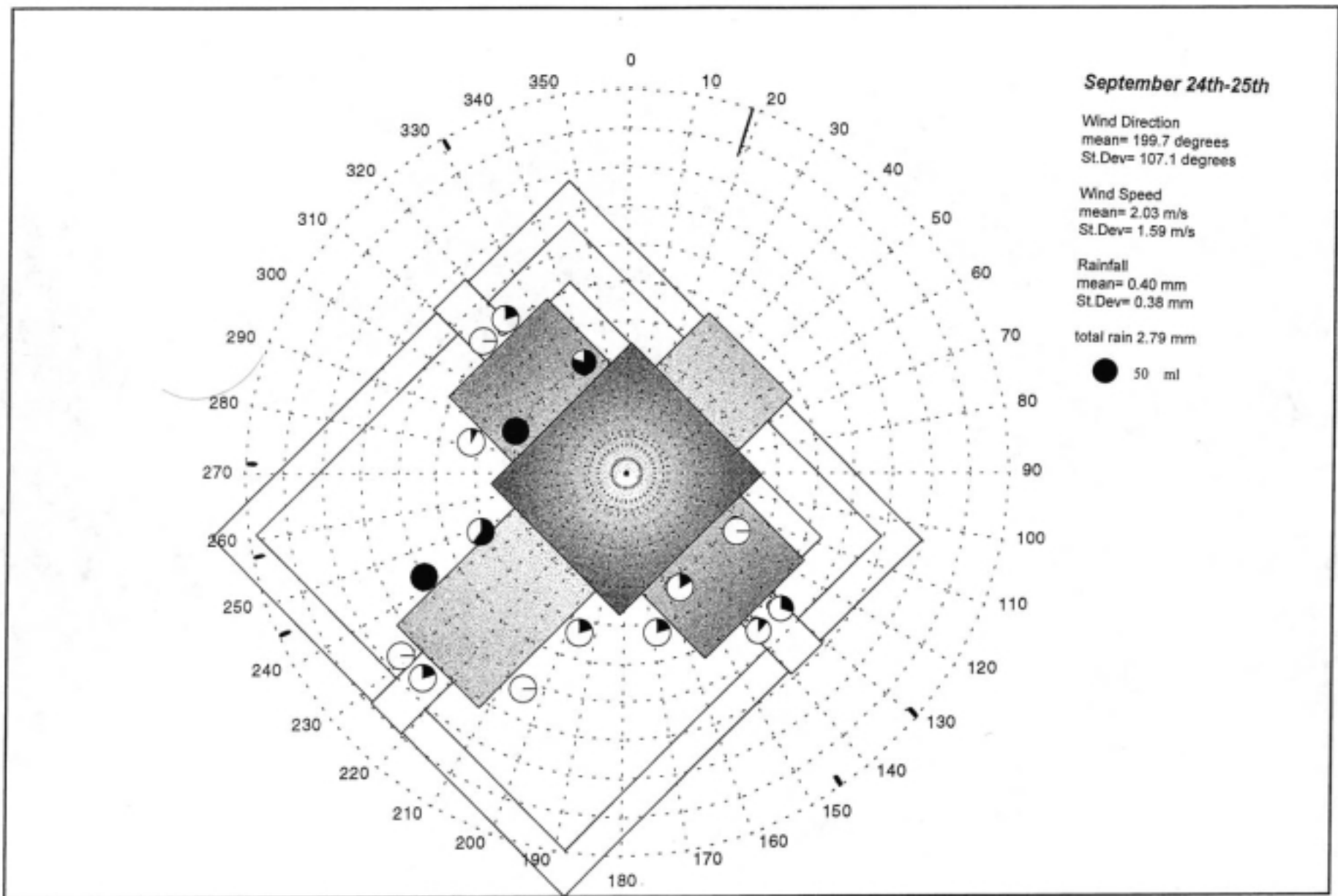


Figure 5.8 Correlation between meteorological data and rain flux data (episode #16)

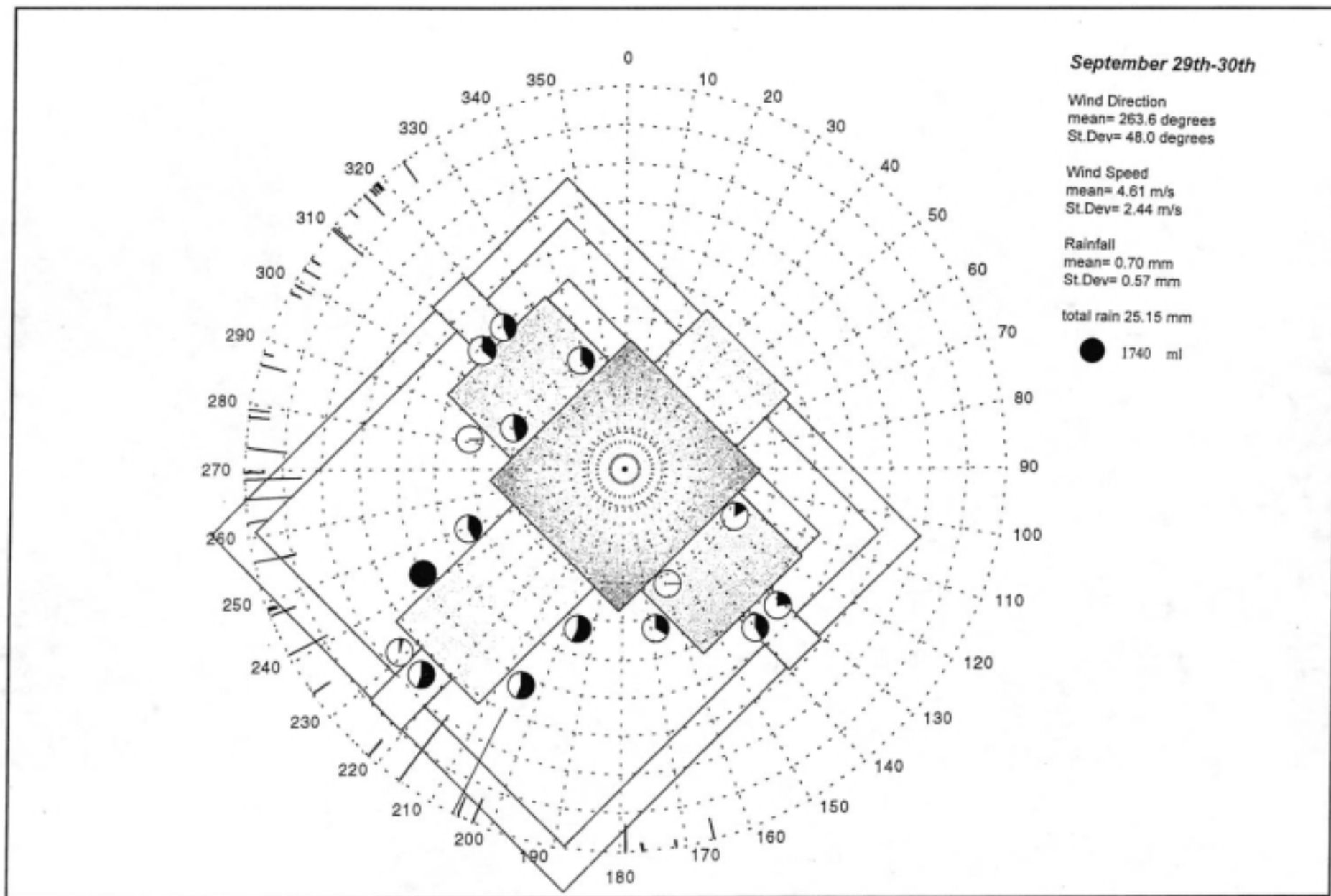


Figure 5.8 Correlation between meteorological data and rain flux data (episode #17)

Table 4-1 Meteorological Data for Intervals with Rainfall

| Episode number and date | Time          | Rainfall | Max wind speed | Direction sector for max wind speed | Eight-bin frequency for wind direction |       |       |       |       |       |       |       | Average wind speed | Mean wind direction | Wind direction std dev. | Direction sector for mean wind | Direction sector with highest frequency |
|-------------------------|---------------|----------|----------------|-------------------------------------|--|-------|-------|-------|-------|-------|-------|-------|--------------------|---------------------|-------------------------|--------------------------------|---|
|                         |               | mm       | m/s            |                                     | 1                                      | 2     | 3     | 4     | 5     | 6     | 7     | 8     | m/s                | degrees             | degrees                 |                                |   |
| 1. 07/24/99             | 900           | 2.032    | 7.4            | 7                                   | 0.011                                  | 0     | 0.011 | 0     | 0     | 0.144 | 0.677 | 0.155 | 4.1                | 272.2               | 26.8                    | 7                              | 7                                       |
| 2. 07/28/99             | 1215          | 2.794    | 18.4           | 8                                   | 0.011                                  | 0     | 0.144 | 0.355 | 0.011 | 0     | 0.078 | 0.4   | 6.4                | 44.0                | 97.5                    | 2                              | 8                                       |
|                         | 07/28/99 1230 | 15.240   | 14.5           | 8                                   | 0.178                                  | 0     | 0     | 0     | 0     | 0     | 0.111 | 0.71  | 9.0                | 318.8               | 19.2                    | 8                              | 8                                       |
|                         | 07/28/99 1245 | 6.604    | 8.8            | 8                                   | 0.411                                  | 0.355 | 0.011 | 0.011 | 0     | 0     | 0.078 | 0.133 | 3.7                | 5.3                 | 41.1                    | 1                              | 1                                       |
|                         | 07/28/99 1300 | 0.762    | 2.5            | 2                                   | 0                                      | 0.277 | 0.488 | 0.233 | 0     | 0     | 0     | 0     | 1.6                | 86.5                | 29.4                    | 3                              | 3                                       |
|                         | 07/28/99 1315 | 1.524    | 12.8           | 7                                   | 0                                      | 0.011 | 0.033 | 0.067 | 0.022 | 0.377 | 0.466 | 0.022 | 5.8                | 245.3               | 40.4                    | 6                              | 7                                       |
|                         | 07/28/99 1330 | 5.080    | 10.1           | 7                                   | 0                                      | 0     | 0     | 0     | 0     | 0.322 | 0.599 | 0.078 | 3.5                | 259.6               | 21.0                    | 7                              | 7                                       |
|                         | 07/28/99 1345 | 1.270    | 3.5            | 7                                   | 0.055                                  | 0.111 | 0.266 | 0.388 | 0.044 | 0.011 | 0.111 | 0.011 | 1.2                | 105.4               | 61.2                    | 3                              | 4                                       |
|                         | 07/28/99 1400 | 1.016    | 2.8            | 4                                   | 0                                      | 0     | 0.289 | 0.688 | 0.011 | 0.011 | 0     | 0     | 1.5                | 123.6               | 23.0                    | 4                              | 4                                       |
|                         | 07/28/99 1415 | 1.270    | 2.4            | 7                                   | 0.233                                  | 0     | 0.055 | 0.067 | 0.011 | 0.033 | 0.333 | 0.244 | 1.5                | 304.0               | 60.7                    | 8                              | 7                                       |
|                         | 07/28/99 1430 | 5.334    | 3.8            | 1                                   | 0.61                                   | 0.011 | 0     | 0     | 0     | 0     | 0     | 0.311 | 1.8                | 347.1               | 15.3                    | 1                              | 1                                       |
|                         | 07/28/99 1445 | 9.910    | 5.1            | 7                                   | 0.1                                    | 0     | 0     | 0     | 0.044 | 0.067 | 0.566 | 0.222 | 2.7                | 279.3               | 38.9                    | 7                              | 7                                       |
|                         | 07/28/99 1500 | 4.064    | 4.1            | 4                                   | 0                                      | 0.011 | 0.033 | 0.677 | 0.133 | 0.078 | 0.044 | 0.022 | 2.5                | 153.9               | 40.4                    | 4                              | 4                                       |
|                         | 07/28/99 1515 | 1.270    | 6.1            | 4                                   | 0                                      | 0     | 0     | 0.733 | 0.233 | 0.033 | 0     | 0     | 3.8                | 151.8               | 17.2                    | 4                              | 4                                       |
|                         | 07/28/99 1530 | 0.508    | 4.7            | 4                                   | 0.011                                  | 0     | 0.044 | 0.444 | 0.133 | 0.089 | 0.244 | 0.033 | 2.1                | 182.6               | 64.6                    | 5                              | 4                                       |
|                         | 07/29/99 130  | 0.254    | 2.8            | 4                                   | 0.011                                  | 0     | 0.011 | 0.733 | 0.089 | 0.078 | 0.078 | 0     | 1.7                | 150.2               | 41.5                    | 4                              | 4                                       |
|                         | 07/29/99 200  | 1.270    | 13.4           | 1                                   | 0.322                                  | 0.033 | 0.033 | 0.522 | 0.033 | 0     | 0     | 0.033 | 3.7                | 94.8                | 77.1                    | 3                              | 4                                       |
|                         | 07/29/99 215  | 12.450   | 11.5           | 8                                   | 0.599                                  | 0.155 | 0.033 | 0     | 0     | 0     | 0.011 | 0.144 | 6.6                | 1.4                 | 27.2                    | 1                              | 1                                       |
|                         | 07/29/99 230  | 2.794    | 10.5           | 2                                   | 0.388                                  | 0.522 | 0.033 | 0     | 0     | 0     | 0.011 | 0.044 | 5.7                | 22.8                | 24.7                    | 2                              | 2                                       |
|                         | 07/29/99 245  | 1.270    | 7.0            | 1                                   | 0.477                                  | 0.444 | 0.033 | 0     | 0     | 0     | 0     | 0.044 | 3.5                | 24.4                | 24.9                    | 2                              | 1                                       |
|                         | 07/29/99 300  | 1.524    | 8.2            | 1                                   | 0.344                                  | 0.566 | 0.055 | 0.011 | 0     | 0     | 0     | 0.022 | 3.8                | 30.8                | 24.4                    | 2                              | 2                                       |

Table 4.1 Meteorological Data for Intervals with Rainfall

44

| Episode number and date | Time | Rainfall<br>mm | Max wind speed<br>m/s | Direction sector for max wind speed | Eight-bin frequency for wind direction |       |       |       |       |       |       |       | Average wind speed<br>m/s | Mean wind direction<br>degrees | Wind direction std dev.<br>degrees | Direction sector for mean wind | Direction sector with highest frequency |
|-------------------------|------|----------------|-----------------------|-------------------------------------|--|-------|-------|-------|-------|-------|-------|-------|---------------------------|--------------------------------|------------------------------------|--------------------------------|---|
|                         |      |                |                       |                                     | 1                                      | 2     | 3     | 4     | 5     | 6     | 7     | 8     |                           |                                |                                    |                                |   |
| 07/29/99                | 315  | 1.270          | 6.5                   | 2                                   | 0.466                                  | 0.444 | 0.044 | 0.011 | 0     | 0     | 0.011 | 0.022 | 3.3                       | 22.7                           | 27.5                               | 2                              | 1                                       |
| 07/29/99                | 330  | 1.524          | 3.0                   | 2                                   | 0.511                                  | 0.311 | 0     | 0     | 0     | 0     | 0     | 0.178 | 2.0                       | 4.5                            | 26.0                               | 1                              | 1                                       |
| 07/29/99                | 345  | 1.778          | 3.8                   | 3                                   | 0.144                                  | 0.444 | 0.4   | 0     | 0     | 0     | 0     | 0.011 | 2.3                       | 55.6                           | 27.6                               | 2                              | 2                                       |
| 07/29/99                | 400  | 1.270          | 1.7                   | 3                                   | 0.166                                  | 0.211 | 0.4   | 0.2   | 0.011 | 0.011 | 0     | 0     | 0.9                       | 77.4                           | 43.7                               | 3                              | 3                                       |
| 07/29/99                | 415  | 1.778          | 5.4                   | 4                                   | 0                                      | 0     | 0.422 | 0.555 | 0.022 | 0     | 0     | 0     | 2.9                       | 117.0                          | 21.9                               | 4                              | 4                                       |
| 07/29/99                | 430  | 0.508          | 9.1                   | 5                                   | 0.011                                  | 0     | 0.044 | 0.733 | 0.2   | 0.011 | 0     | 0     | 4.8                       | 145.7                          | 23.1                               | 4                              | 4                                       |
| 3. 08/01/99             | 800  | 3.048          | 6.5                   | 7                                   | 0                                      | 0     | 0     | 0     | 0     | 0.022 | 0.799 | 0.178 | 4.0                       | 278.8                          | 15.3                               | 7                              | 7                                       |
| 08/01/99                | 815  | 8.130          | 3.2                   | 8                                   | 0.178                                  | 0.089 | 0.044 | 0.011 | 0     | 0     | 0.122 | 0.533 | 1.6                       | 328.5                          | 42.7                               | 8                              | 8                                       |
| 08/01/99                | 830  | 2.794          | 3.5                   | 8                                   | 0.178                                  | 0     | 0     | 0     | 0     | 0     | 0.266 | 0.555 | 1.9                       | 312.2                          | 24.0                               | 8                              | 8                                       |
| 08/01/99                | 845  | 3.302          | 2.2                   | 8                                   | 0.721                                  | 0.078 | 0.011 | 0     | 0     | 0     | 0     | 0.144 | 1.2                       | 353.7                          | 22.1                               | 1                              | 1                                       |
| 08/01/99                | 900  | 2.032          | 3.2                   | 1                                   | 0.511                                  | 0     | 0     | 0     | 0     | 0     | 0.033 | 0.433 | 2.2                       | 335.2                          | 19.5                               | 8                              | 1                                       |
| 08/01/99                | 915  | 1.270          | 3.8                   | 8                                   | 0.622                                  | 0.055 | 0.011 | 0.011 | 0     | 0     | 0     | 0.233 | 2.1                       | 354.0                          | 23.7                               | 1                              | 1                                       |
| 08/01/99                | 930  | 1.524          | 2.4                   | 1                                   | 0.633                                  | 0.155 | 0     | 0.011 | 0     | 0     | 0.011 | 0.111 | 1.4                       | 3.8                            | 25.3                               | 1                              | 1                                       |
| 08/01/99                | 945  | 0.254          | 2.6                   | 3                                   | 0.266                                  | 0.544 | 0.166 | 0     | 0     | 0     | 0     | 0.011 | 1.5                       | 38.9                           | 27.7                               | 2                              | 2                                       |
| 4. 08/05/99             | 45   | 0.254          | 5.4                   | 1                                   | 0.511                                  | 0     | 0     | 0     | 0     | 0     | 0     | 0.466 | 3.4                       | 338.8                          | 10.9                               | 1                              | 1                                       |
| 5. 08/08/99             | 315  | 0.254          | 2.1                   | 8                                   | 0.233                                  | 0.011 | 0     | 0     | 0     | 0     | 0.133 | 0.622 | 1.3                       | 319.7                          | 25.5                               | 8                              | 8                                       |
| 08/08/99                | 330  | 2.286          | 2.8                   | 8                                   | 0.133                                  | 0.067 | 0.166 | 0.166 | 0     | 0.055 | 0.211 | 0.2   | 1.2                       | 345.3                          | 91.5                               | 1                              | 7                                       |
| 08/08/99                | 345  | 0.254          | 1.9                   | 4                                   | 0.011                                  | 0.022 | 0.433 | 0.533 | 0     | 0     | 0     | 0     | 1.4                       | 109.9                          | 19.6                               | 3                              | 4                                       |
| 08/08/99                | 715  | 0.254          | 2.6                   | 5                                   | 0                                      | 0.011 | 0.033 | 0.266 | 0.078 | 0.166 | 0.388 | 0.044 | 1.6                       | 217.8                          | 64.1                               | 6                              | 7                                       |
| 6. 08/10/99             | 1600 | 0.254          | 3.4                   | 6                                   | 0.033                                  | 0.067 | 0.011 | 0.233 | 0.2   | 0.289 | 0.144 | 0.022 | 1.9                       | 195.6                          | 65.6                               | 5                              | 6                                       |
| 08/10/99                | 1700 | 0.508          | 5.5                   | 5                                   | 0                                      | 0     | 0.033 | 0.466 | 0.255 | 0.166 | 0.067 | 0.011 | 3.0                       | 168.6                          | 45.4                               | 5                              | 4                                       |

Table 4.1 Meteorological Data for Intervals with Rainfall

| Episode number and date | Time | Rainfall | Max wind speed | Direction sector for max wind speed | Eight-bin frequency for wind direction |       |       |       |       |       |       |       | Average wind speed | Mean wind direction | Wind direction std dev. | Direction sector for mean wind | Direction sector with highest frequency |
|-------------------------|------|----------|----------------|-------------------------------------|--|-------|-------|-------|-------|-------|-------|-------|--------------------|---------------------|-------------------------|--------------------------------|---|
|                         |      | mm       | m/s            |                                     | 1                                      | 2     | 3     | 4     | 5     | 6     | 7     | 8     | m/s                | degrees             | degrees                 |                                |   |
| 08/13/99                | 1100 | 0.762    | 5.2            | 5                                   | 0.033                                  | 0.011 | 0.011 | 0.333 | 0.178 | 0.266 | 0.133 | 0.033 | 2.7                | 192.1               | 61.4                    | 5                              | 4                                       |
| 08/13/99                | 1115 | 0.254    | 4.2            | 4                                   | 0                                      | 0.022 | 0.033 | 0.422 | 0.3   | 0.144 | 0.067 | 0.011 | 2.4                | 168.3               | 45.9                    | 5                              | 4                                       |
| 7. 08/13/99             | 1630 | 3.048    | 7.1            | 1                                   | 0.222                                  | 0.166 | 0.033 | 0     | 0     | 0     | 0.011 | 0.555 | 3.6                | 343.2               | 35.5                    | 1                              | 8                                       |
| 08/13/99                | 1645 | 2.794    | 16.8           | 8                                   | 0.633                                  | 0.067 | 0.022 | 0     | 0     | 0     | 0     | 0.233 | 6.5                | 353.4               | 25.2                    | 1                              | 1                                       |
| 08/13/99                | 1700 | 2.794    | 3.8            | 8                                   | 0.067                                  | 0.055 | 0.067 | 0.122 | 0.033 | 0.022 | 0.3   | 0.333 | 2.0                | 295.2               | 73.1                    | 8                              | 5                                       |
| 08/13/99                | 1715 | 1.270    | 3.7            | 1                                   | 0.522                                  | 0.2   | 0.055 | 0     | 0     | 0     | 0     | 0.155 | 1.9                | 7.1                 | 31.9                    | 1                              | 1                                       |
| 08/13/99                | 1915 | 0.508    | 6.0            | 6                                   | 0.011                                  | 0     | 0.022 | 0.2   | 0.244 | 0.322 | 0.178 | 0.022 | 2.9                | 206.1               | 52.1                    | 6                              | 6                                       |
| 08/13/99                | 2015 | 1.524    | 6.2            | 7                                   | 0.011                                  | 0     | 0.011 | 0.022 | 0.011 | 0.144 | 0.721 | 0.078 | 3.0                | 268.6               | 31.5                    | 7                              | 7                                       |
| 08/13/99                | 2100 | 0.254    | 3.0            | 6                                   | 0                                      | 0     | 0.011 | 0.111 | 0.067 | 0.322 | 0.433 | 0.055 | 1.9                | 241.0               | 41.7                    | 6                              | 7                                       |
| 08/13/99                | 2115 | 1.270    | 3.2            | 7                                   | 0                                      | 0.011 | 0.011 | 0.011 | 0.022 | 0.377 | 0.544 | 0.022 | 1.8                | 249.2               | 29.7                    | 7                              | 7                                       |
| 08/13/99                | 2200 | 0.254    | 3.5            | 7                                   | 0                                      | 0.011 | 0.044 | 0.455 | 0.266 | 0.055 | 0.144 | 0.022 | 1.7                | 164.1               | 52.6                    | 5                              | 4                                       |
| 08/14/99                | 1645 | 0.508    | 8.4            | 7                                   | 0.022                                  | 0.011 | 0     | 0     | 0.011 | 0.133 | 0.777 | 0.044 | 5.2                | 266.7               | 25.3                    | 7                              | 7                                       |
| 08/14/99                | 1700 | 1.016    | 7.1            | 8                                   | 0.011                                  | 0     | 0     | 0     | 0     | 0.055 | 0.688 | 0.244 | 4.5                | 281.3               | 19.2                    | 7                              | 7                                       |
| 08/16/99                | 615  | 0.254    | 1.5            | 4                                   | 0.033                                  | 0.033 | 0.1   | 0.377 | 0.055 | 0.089 | 0.266 | 0.044 | 0.7                | 178.6               | 81.8                    | 5                              | 4                                       |
| 8. 08/24/99             | 1700 | 1.016    | 14.9           | 5                                   | 0                                      | 0     | 0.022 | 0.233 | 0.511 | 0.211 | 0.022 | 0     | 7.3                | 177.5               | 32.7                    | 5                              | 5                                       |
| 08/24/99                | 1715 | 15.750   | 12.5           | 5                                   | 0                                      | 0     | 0.311 | 0.311 | 0.333 | 0.044 | 0     | 0     | 5.3                | 139.5               | 39.0                    | 4                              | 5                                       |
| 08/24/99                | 1730 | 0.762    | 4.6            | 2                                   | 0                                      | 0.355 | 0.622 | 0.022 | 0     | 0     | 0     | 0     | 2.3                | 75.8                | 16.7                    | 3                              | 3                                       |
| 08/24/99                | 1745 | 1.016    | 2.0            | 3                                   | 0.067                                  | 0.144 | 0.089 | 0.033 | 0.033 | 0.055 | 0.488 | 0.089 | 0.9                | 292.1               | 72.3                    | 7                              | 7                                       |
| 08/24/99                | 1800 | 1.016    | 2.2            | 4                                   | 0                                      | 0     | 0.289 | 0.666 | 0.033 | 0     | 0.011 | 0     | 1.4                | 123.5               | 24.1                    | 4                              | 4                                       |
| 08/24/99                | 1815 | 1.016    | 2.2            | 4                                   | 0                                      | 0.155 | 0.178 | 0.655 | 0.011 | 0     | 0     | 0     | 1.6                | 114.8               | 34.1                    | 4                              | 4                                       |
| 08/24/99                | 1830 | 0.254    | 3.4            | 2                                   | 0.022                                  | 0.866 | 0.111 | 0     | 0     | 0     | 0     | 0     | 2.1                | 51.4                | 12.9                    | 2                              | 2                                       |

Table 4.1 Meteorological Data for Intervals with Rainfall

| Episode number and date | Time | Rainfall | Max wind speed | Direction sector for max wind speed | Eight-bin frequency for wind direction |       |       |       |       |       |       |       | Average wind speed | Mean wind direction | Wind direction std dev. | Direction sector for mean wind | Direction sector with highest frequency |
|-------------------------|------|----------|----------------|-------------------------------------|--|-------|-------|-------|-------|-------|-------|-------|--------------------|---------------------|-------------------------|--------------------------------|---|
|                         |      | mm       | m/s            |                                     | 1                                      | 2     | 3     | 4     | 5     | 6     | 7     | 8     | m/s                | degrees             | degrees                 |                                |   |
| 08/24/99                | 1845 | 0.254    | 2.9            | 2                                   | 0.022                                  | 0.289 | 0.599 | 0.089 | 0     | 0     | 0     | 0     | 1.9                | 78.2                | 26.7                    | 3                              | 3                                       |
| 08/24/99                | 1900 | 0.254    | 3.6            | 2                                   | 0.222                                  | 0.71  | 0.044 | 0     | 0     | 0     | 0     | 0.011 | 2.4                | 35.0                | 18.9                    | 2                              | 2                                       |
| 08/25/99                | 430  | 0.254    | 4.0            | 4                                   | 0                                      | 0     | 0.078 | 0.888 | 0.033 | 0     | 0     | 0     | 2.8                | 133.6               | 15.6                    | 4                              | 4                                       |
| 08/25/99                | 830  | 0.254    | 4.1            | 4                                   | 0                                      | 0.022 | 0.433 | 0.533 | 0.011 | 0     | 0     | 0     | 2.6                | 112.9               | 19.9                    | 4                              | 4                                       |
| 08/25/99                | 900  | 0.508    | 3.9            | 3                                   | 0                                      | 0.067 | 0.81  | 0.111 | 0.011 | 0     | 0     | 0     | 2.4                | 95.4                | 18.7                    | 3                              | 3                                       |
| 08/25/99                | 915  | 1.016    | 3.8            | 4                                   | 0                                      | 0.022 | 0.699 | 0.277 | 0     | 0     | 0     | 0     | 2.7                | 102.3               | 17.9                    | 3                              | 3                                       |
| 08/25/99                | 1000 | 2.032    | 2.5            | 3                                   | 0.011                                  | 0.2   | 0.577 | 0.2   | 0.011 | 0     | 0     | 0     | 1.4                | 89.7                | 29.1                    | 3                              | 3                                       |
| 08/25/99                | 1015 | 1.524    | 2.7            | 3                                   | 0                                      | 0.1   | 0.888 | 0.011 | 0     | 0     | 0     | 0     | 1.9                | 85.6                | 14.0                    | 3                              | 3                                       |
| 08/25/99                | 1030 | 2.794    | 2.7            | 3                                   | 0                                      | 0.011 | 0.388 | 0.544 | 0     | 0     | 0.011 | 0.044 | 1.5                | 113.2               | 33.9                    | 4                              | 4                                       |
| 08/25/99                | 1045 | 0.762    | 4.4            | 3                                   | 0                                      | 0     | 0.488 | 0.511 | 0     | 0     | 0     | 0     | 2.3                | 110.2               | 18.5                    | 3                              | 4                                       |
| 08/25/99                | 1100 | 0.254    | 4.0            | 4                                   | 0                                      | 0.033 | 0.344 | 0.577 | 0.044 | 0     | 0     | 0     | 2.4                | 117.1               | 23.0                    | 4                              | 4                                       |
| 9. 08/26/99             | 215  | 0.254    | 2.0            | 6                                   | 0.011                                  | 0     | 0     | 0.033 | 0.022 | 0.244 | 0.666 | 0.022 | 1.5                | 251.4               | 26.9                    | 7                              | 7                                       |
| 08/26/99                | 230  | 0.508    | 1.9            | 4                                   | 0                                      | 0.033 | 0.133 | 0.366 | 0.189 | 0.122 | 0.144 | 0.011 | 1.1                | 164.4               | 60.6                    | 5                              | 4                                       |
| 08/26/99                | 245  | 0.254    | 1.7            | 4                                   | 0                                      | 0.011 | 0.344 | 0.622 | 0.011 | 0     | 0.011 | 0     | 1.0                | 118.4               | 25.7                    | 4                              | 4                                       |
| 08/26/99                | 515  | 2.032    | 1.9            | 3                                   | 0.011                                  | 0.255 | 0.511 | 0.222 | 0     | 0     | 0     | 0     | 1.2                | 89.1                | 27.2                    | 3                              | 3                                       |
| 08/26/99                | 530  | 1.016    | 1.8            | 3                                   | 0                                      | 0.355 | 0.566 | 0.078 | 0     | 0     | 0     | 0     | 1.3                | 74.2                | 26.5                    | 3                              | 3                                       |
| 08/26/99                | 545  | 1.016    | 2.0            | 2                                   | 0.055                                  | 0.422 | 0.488 | 0.011 | 0     | 0     | 0     | 0.022 | 1.3                | 63.0                | 27.7                    | 2                              | 3                                       |
| 08/26/99                | 600  | 0.254    | 1.6            | 2                                   | 0.289                                  | 0.533 | 0.033 | 0     | 0     | 0     | 0     | 0.144 | 1.1                | 17.9                | 31.2                    | 1                              | 2                                       |
| 08/26/99                | 645  | 0.254    | 1.0            | 8                                   | 0.222                                  | 0.022 | 0.144 | 0.189 | 0.011 | 0.022 | 0.067 | 0.322 | 0.2                | 19.5                | 72.8                    | 1                              | 8                                       |
| 08/26/99                | 700  | 1.016    | 1.3            | 5                                   | 0                                      | 0.011 | 0.144 | 0.721 | 0.044 | 0.044 | 0.033 | 0     | 0.7                | 130.8               | 31.7                    | 4                              | 4                                       |
| 08/26/99                | 715  | 2.032    | 2.0            | 7                                   | 0                                      | 0     | 0     | 0.055 | 0     | 0.078 | 0.788 | 0.078 | 1.3                | 266.4               | 30.5                    | 7                              | 7                                       |

Table 4.1 Meteorological Data for Intervals with Rainfall

| Episode number and date | Time | Rainfall | Max wind speed | Direction sector for max wind speed | Eight-bin frequency for wind direction |       |       |       |       |       |       |       | Average wind speed | Mean wind direction | Wind direction std dev. | Direction sector for mean wind | Direction sector with highest frequency |
|-------------------------|------|----------|----------------|-------------------------------------|--|-------|-------|-------|-------|-------|-------|-------|--------------------|---------------------|-------------------------|--------------------------------|---|
|                         |      | mm       | m/s            |                                     | 1                                      | 2     | 3     | 4     | 5     | 6     | 7     | 8     | m/s                | degrees             | degrees                 |                                |   |
| 08/26/99                | 730  | 3.556    | 3.8            | 4                                   | 0                                      | 0.022 | 0.122 | 0.61  | 0.078 | 0.067 | 0.078 | 0.022 | 1.7                | 144.5               | 49.3                    | 4                              | 4                                       |
| 08/26/99                | 745  | 0.762    | 4.1            | 4                                   | 0                                      | 0     | 0.011 | 0.877 | 0.111 | 0     | 0     | 0     | 2.5                | 144.7               | 14.1                    | 4                              | 4                                       |
| 08/26/99                | 800  | 0.508    | 2.8            | 7                                   | 0.044                                  | 0.055 | 0.089 | 0.178 | 0.144 | 0.178 | 0.289 | 0.022 | 1.2                | 206.1               | 73.7                    | 6                              | 7                                       |
| 08/26/99                | 815  | 0.254    | 2.2            | 4                                   | 0.033                                  | 0.022 | 0.055 | 0.455 | 0.011 | 0.044 | 0.344 | 0.033 | 0.9                | 177.3               | 84.3                    | 5                              | 4                                       |
| 10. 08/26/99            | 1215 | 0.254    | 3.1            | 7                                   | 0.022                                  | 0.033 | 0     | 0     | 0.022 | 0.033 | 0.699 | 0.189 | 1.9                | 277.8               | 32.6                    | 7                              | 7                                       |
| 08/26/99                | 1230 | 0.508    | 4.2            | 7                                   | 0.133                                  | 0     | 0.011 | 0     | 0     | 0.011 | 0.344 | 0.499 | 2.5                | 305.6               | 27.4                    | 8                              | 8                                       |
| 08/26/99                | 1300 | 1.270    | 4.4            | 8                                   | 0.189                                  | 0     | 0     | 0     | 0     | 0.011 | 0.067 | 0.721 | 2.2                | 318.4               | 20.2                    | 8                              | 8                                       |
| 11. 08/27/99            | 730  | 0.254    | 2.0            | 7                                   | 0.1                                    | 0.011 | 0.033 | 0.044 | 0.011 | 0.122 | 0.466 | 0.211 | 0.9                | 277.6               | 52.7                    | 7                              | 7                                       |
| 08/27/99                | 745  | 0.254    | 2.5            | 6                                   | 0                                      | 0     | 0.011 | 0.067 | 0.033 | 0.344 | 0.499 | 0.044 | 1.6                | 244.7               | 34.5                    | 6                              | 7                                       |
| 08/27/99                | 815  | 0.254    | 2.4            | 4                                   | 0                                      | 0.011 | 0.011 | 0.355 | 0.289 | 0.155 | 0.166 | 0.011 | 1.6                | 181.5               | 50.2                    | 5                              | 4                                       |
| 12. 09/05/99            | 230  | 0.254    | 3.6            | 3                                   | 0.011                                  | 0.566 | 0.411 | 0.011 | 0     | 0     | 0     | 0     | 2.5                | 64.0                | 16.3                    | 2                              | 2                                       |
| 13. 09/13/99            | 1730 | 0.254    | 8.0            | 8                                   | 0.444                                  | 0.011 | 0     | 0     | 0     | 0.011 | 0     | 0.522 | 5.0                | 336.5               | 20.3                    | 8                              | 8                                       |
| 09/13/99                | 1745 | 0.254    | 6.9            | 8                                   | 0.133                                  | 0     | 0     | 0     | 0     | 0.011 | 0     | 0.855 | 4.5                | 322.2               | 15.1                    | 8                              | 8                                       |
| 09/13/99                | 1800 | 0.254    | 4.8            | 8                                   | 0.166                                  | 0.033 | 0.022 | 0     | 0.033 | 0.1   | 0.033 | 0.61  | 2.2                | 316.2               | 45.4                    | 8                              | 8                                       |
| 09/13/99                | 1830 | 0.254    | 3.6            | 7                                   | 0.178                                  | 0     | 0.011 | 0     | 0     | 0.033 | 0.055 | 0.721 | 2.2                | 320.0               | 27.2                    | 8                              | 8                                       |
| 09/13/99                | 1845 | 0.254    | 3.6            | 8                                   | 0.1                                    | 0.011 | 0     | 0     | 0.144 | 0.222 | 0.067 | 0.455 | 1.8                | 284.1               | 61.7                    | 7                              | 8                                       |
| 14. 09/16/99            | 1130 | 0.254    | 7.6            | 1                                   | 0.755                                  | 0.189 | 0     | 0     | 0     | 0     | 0     | 0.022 | 5.1                | 9.0                 | 14.0                    | 1                              | 1                                       |
| 09/16/99                | 1145 | 0.254    | 8.0            | 1                                   | 0.622                                  | 0.3   | 0     | 0     | 0     | 0     | 0     | 0.022 | 4.7                | 12.4                | 17.2                    | 1                              | 1                                       |
| 09/16/99                | 1200 | 0.508    | 6.9            | 1                                   | 0.755                                  | 0.133 | 0     | 0     | 0     | 0     | 0     | 0.044 | 4.7                | 7.4                 | 15.7                    | 1                              | 1                                       |
| 09/16/99                | 1215 | 0.254    | 7.2            | 1                                   | 0.544                                  | 0.244 | 0     | 0     | 0     | 0     | 0     | 0.022 | 4.3                | 12.3                | 15.4                    | 1                              | 1                                       |
| 09/16/99                | 1230 | 0.254    | 7.9            | 1                                   | 0.655                                  | 0.122 | 0.011 | 0.022 | 0     | 0     | 0     | 0.011 | 4.6                | 11.2                | 23.1                    | 1                              | 1                                       |

Table 4.1 Meteorological Data for Intervals with Rainfall

| Episode number and date | Time | Rainfall<br>mm | Max wind speed<br>m/s | Direction sector for max wind speed | Eight-bin frequency for wind direction |       |       |       |       |       |       |       | Average wind speed<br>m/s | Mean wind direction<br>degrees | Wind direction std dev.<br>degrees | Direction sector for mean wind | Direction sector with highest frequency |
|-------------------------|------|----------------|-----------------------|-------------------------------------|--|-------|-------|-------|-------|-------|-------|-------|---------------------------|--------------------------------|------------------------------------|--------------------------------|---|
|                         |      |                |                       |                                     | 1                                      | 2     | 3     | 4     | 5     | 6     | 7     | 8     |                           |                                |                                    |                                |   |
| 09/16/99                | 1300 | 0.254          | 7.3                   | 1                                   | 0.677                                  | 0.1   | 0     | 0     | 0     | 0     | 0     | 0.033 | 4.9                       | 2.7                            | 14.7                               | 1                              | 1                                       |
| 09/16/99                | 1315 | 0.254          | 9.2                   | 1                                   | 0.633                                  | 0.067 | 0     | 0     | 0     | 0     | 0.011 | 0.078 | 4.1                       | 0.9                            | 19.9                               | 1                              | 1                                       |
| 09/16/99                | 1330 | 0.254          | 7.2                   | 1                                   | 0.555                                  | 0.189 | 0     | 0     | 0     | 0     | 0     | 0.055 | 4.2                       | 8.4                            | 18.7                               | 1                              | 1                                       |
| 09/16/99                | 1415 | 0.254          | 6.0                   | 2                                   | 0.655                                  | 0.055 | 0     | 0     | 0     | 0     | 0     | 0.055 | 3.8                       | 4.0                            | 13.4                               | 1                              | 1                                       |
| 09/16/99                | 1500 | 0.254          | 7.9                   | 1                                   | 0.733                                  | 0.133 | 0.011 | 0     | 0     | 0     | 0     | 0.022 | 4.8                       | 7.8                            | 15.8                               | 1                              | 1                                       |
| 09/16/99                | 1515 | 0.254          | 7.2                   | 2                                   | 0.666                                  | 0.044 | 0     | 0     | 0     | 0     | 0.011 | 0.067 | 4.9                       | 1.0                            | 16.6                               | 1                              | 1                                       |
| 09/16/99                | 1645 | 0.254          | 8.5                   | 8                                   | 0.4                                    | 0.011 | 0     | 0     | 0     | 0.011 | 0.067 | 0.511 | 4.7                       | 327.9                          | 22.9                               | 8                              | 8                                       |
| 15. 09/20/99            | 1115 | 0.254          | 3.5                   | 7                                   | 0.011                                  | 0.011 | 0     | 0.022 | 0.166 | 0.033 | 0.544 | 0.211 | 2.2                       | 273.8                          | 48.9                               | 7                              | 7                                       |
| 09/20/99                | 1145 | 0.762          | 6.3                   | 8                                   | 0.033                                  | 0     | 0     | 0     | 0     | 0.011 | 0.344 | 0.61  | 4.1                       | 298.8                          | 19.1                               | 8                              | 8                                       |
| 09/20/99                | 1200 | 1.016          | 5.6                   | 8                                   | 0                                      | 0     | 0     | 0     | 0     | 0     | 0.344 | 0.655 | 3.9                       | 296.3                          | 10.7                               | 8                              | 8                                       |
| 09/20/99                | 1215 | 0.762          | 3.5                   | 7                                   | 0.022                                  | 0     | 0     | 0     | 0     | 0.011 | 0.599 | 0.366 | 2.2                       | 291.4                          | 16.1                               | 7                              | 7                                       |
| 09/20/99                | 1230 | 0.508          | 3.2                   | 8                                   | 0.011                                  | 0     | 0     | 0     | 0.011 | 0.022 | 0.688 | 0.266 | 2.2                       | 287.0                          | 21.5                               | 7                              | 7                                       |
| 09/20/99                | 1245 | 0.254          | 3.3                   | 7                                   | 0.033                                  | 0.011 | 0.011 | 0     | 0.022 | 0.011 | 0.544 | 0.366 | 2.2                       | 292.3                          | 29.0                               | 7                              | 7                                       |
| 09/20/99                | 1300 | 0.254          | 2.4                   | 5                                   | 0.022                                  | 0     | 0     | 0.078 | 0.511 | 0.089 | 0.211 | 0.089 | 1.7                       | 209.1                          | 55.5                               | 6                              | 5                                       |
| 09/20/99                | 1315 | 0.254          | 2.8                   | 5                                   | 0.011                                  | 0     | 0     | 0.011 | 0.855 | 0.055 | 0.067 | 0     | 1.9                       | 186.8                          | 26.8                               | 5                              | 5                                       |
| 09/20/99                | 1330 | 0.254          | 3.0                   | 5                                   | 0.011                                  | 0     | 0.011 | 0.067 | 0.855 | 0.022 | 0.022 | 0.011 | 1.9                       | 180.0                          | 26.7                               | 5                              | 5                                       |
| 09/20/99                | 1345 | 0.254          | 2.8                   | 5                                   | 0                                      | 0     | 0.011 | 0.011 | 0.932 | 0.044 | 0     | 0     | 2.2                       | 181.6                          | 13.9                               | 5                              | 5                                       |
| 09/20/99                | 1415 | 0.254          | 2.8                   | 6                                   | 0.022                                  | 0     | 0     | 0.089 | 0.61  | 0.155 | 0.1   | 0.022 | 1.7                       | 193.7                          | 41.5                               | 5                              | 5                                       |
| 09/20/99                | 1445 | 0.254          | 2.9                   | 6                                   | 0                                      | 0     | 0.067 | 0.022 | 0.322 | 0.166 | 0.255 | 0.166 | 1.8                       | 229.1                          | 63.9                               | 6                              | 5                                       |
| 09/20/99                | 1500 | 0.254          | 4.0                   | 7                                   | 0.044                                  | 0.011 | 0.022 | 0.022 | 0.255 | 0.144 | 0.366 | 0.133 | 2.1                       | 248.8                          | 58.6                               | 7                              | 7                                       |
| 09/20/99                | 1530 | 0.254          | 3.2                   | 5                                   | 0.011                                  | 0     | 0.011 | 0.033 | 0.544 | 0.155 | 0.155 | 0.089 | 1.7                       | 209.3                          | 51.4                               | 6                              | 5                                       |

Table 4.1 Meteorological Data for Intervals with Rainfall

| Episode number and date | Time | Rainfall<br>mm | Max wind speed<br>m/s | Direction sector for max wind speed | Eight-bin frequency for wind direction |       |       |       |       |       |       |       | Average wind speed<br>m/s | Mean wind direction<br>degrees | Wind direction std dev.<br>degrees | Direction sector for mean wind | Direction sector with highest frequency |
|-------------------------|------|----------------|-----------------------|-------------------------------------|--|-------|-------|-------|-------|-------|-------|-------|---------------------------|--------------------------------|------------------------------------|--------------------------------|---|
|                         |      |                |                       |                                     | 1                                      | 2     | 3     | 4     | 5     | 6     | 7     | 8     |                           |                                |                                    |                                |   |
| 09/20/99                | 1545 | 0.254          | 3.2                   | 5                                   | 0                                      | 0     | 0.011 | 0.011 | 0.511 | 0.211 | 0.178 | 0.078 | 1.8                       | 214.2                          | 43.9                               | 6                              | 5                                       |
| 09/20/99                | 1600 | 0.254          | 4.1                   | 5                                   | 0.033                                  | 0.011 | 0     | 0.022 | 0.377 | 0.289 | 0.2   | 0.067 | 2.0                       | 219.5                          | 48.6                               | 6                              | 5                                       |
| 09/20/99                | 1615 | 0.508          | 3.2                   | 7                                   | 0                                      | 0.011 | 0.011 | 0.055 | 0.255 | 0.178 | 0.255 | 0.233 | 1.8                       | 243.3                          | 58.5                               | 6                              | 5&7                                     |
| 09/20/99                | 1645 | 0.508          | 3.3                   | 8                                   | 0.022                                  | 0.022 | 0.033 | 0.044 | 0.244 | 0.166 | 0.2   | 0.266 | 1.6                       | 253.2                          | 65.0                               | 7                              | 8                                       |
| 09/20/99                | 1700 | 0.254          | 2.8                   | 8                                   | 0.033                                  | 0.011 | 0     | 0     | 0.067 | 0.022 | 0.266 | 0.599 | 1.8                       | 296.2                          | 34.2                               | 8                              | 8                                       |
| 09/20/99                | 1715 | 0.254          | 3.9                   | 7                                   | 0.033                                  | 0.011 | 0.011 | 0.011 | 0.033 | 0.044 | 0.4   | 0.455 | 1.9                       | 293.4                          | 36.4                               | 8                              | 8                                       |
| 09/20/99                | 1745 | 0.254          | 4.5                   | 8                                   | 0.033                                  | 0     | 0     | 0     | 0.022 | 0     | 0.388 | 0.544 | 2.1                       | 295.9                          | 25.1                               | 8                              | 8                                       |
| 09/20/99                | 2045 | 1.270          | 5.2                   | 7                                   | 0.067                                  | 0     | 0     | 0     | 0     | 0     | 0.2   | 0.733 | 2.9                       | 307.8                          | 18.4                               | 8                              | 8                                       |
| 09/20/99                | 2115 | 0.254          | 4.0                   | 2                                   | 0.466                                  | 0.477 | 0.022 | 0     | 0     | 0     | 0     | 0.011 | 2.6                       | 24.9                           | 21.3                               | 2                              | 2                                       |
| 09/20/99                | 2145 | 0.254          | 4.8                   | 1                                   | 0.633                                  | 0.3   | 0     | 0     | 0     | 0     | 0     | 0     | 3.4                       | 14.1                           | 12.6                               | 1                              | 1                                       |
| 09/21/99                | 115  | 0.254          | 3.6                   | 1                                   | 0.599                                  | 0.355 | 0.011 | 0     | 0     | 0     | 0     | 0.033 | 2.3                       | 14.9                           | 19.8                               | 1                              | 1                                       |
| 09/21/99                | 130  | 0.762          | 2.8                   | 1                                   | 0.633                                  | 0.3   | 0     | 0     | 0     | 0     | 0     | 0.011 | 1.8                       | 14.1                           | 15.6                               | 1                              | 1                                       |
| 09/21/99                | 215  | 0.254          | 2.4                   | 2                                   | 0.255                                  | 0.244 | 0.444 | 0.044 | 0     | 0     | 0     | 0     | 1.3                       | 55.5                           | 35.7                               | 2                              | 3                                       |
| 09/21/99                | 230  | 0.254          | 2.4                   | 2                                   | 0.222                                  | 0.511 | 0.255 | 0     | 0     | 0     | 0     | 0     | 1.4                       | 44.2                           | 31.2                               | 2                              | 2                                       |
| 09/21/99                | 630  | 0.254          | 4.8                   | 2                                   | 0.189                                  | 0.71  | 0.067 | 0.022 | 0     | 0     | 0.011 | 0     | 2.4                       | 40.7                           | 25.1                               | 2                              | 2                                       |
| 16. 09/24/99            | 1800 | 0.254          | 2.5                   | 4                                   | 0.011                                  | 0.011 | 0.178 | 0.455 | 0.233 | 0.067 | 0.033 | 0.011 | 1.3                       | 144.8                          | 43.4                               | 4                              | 4                                       |
| 09/24/99                | 1815 | 0.254          | 7.9                   | 7                                   | 0.011                                  | 0     | 0.011 | 0.166 | 0.1   | 0.122 | 0.511 | 0.078 | 2.8                       | 243.4                          | 56.4                               | 6                              | 7                                       |
| 09/24/99                | 1830 | 0.254          | 9.6                   | 8                                   | 0                                      | 0     | 0.022 | 0.044 | 0.067 | 0.033 | 0.577 | 0.255 | 5.2                       | 272.5                          | 42.9                               | 7                              | 7                                       |
| 09/24/99                | 2130 | 0.254          | 1.6                   | 7                                   | 0.055                                  | 0.089 | 0.166 | 0.477 | 0.089 | 0.011 | 0.1   | 0.011 | 0.8                       | 129.8                          | 60.5                               | 4                              | 4                                       |
| 09/24/99                | 2300 | 0.254          | 2.9                   | 7                                   | 0.011                                  | 0     | 0     | 0.044 | 0.078 | 0.055 | 0.799 | 0.011 | 2.0                       | 257.5                          | 35.1                               | 7                              | 7                                       |
| 09/25/99                | 215  | 1.270          | 1.4                   | 8                                   | 0.355                                  | 0.3   | 0.155 | 0     | 0     | 0     | 0.011 | 0.1   | 0.6                       | 18.2                           | 38.3                               | 1                              | 1                                       |

Table 4.1 Meteorological Data for Intervals with Rainfall

| Episode number and date | Time | Rainfall | Max wind speed | Direction sector for max wind speed | Eight-bin frequency for wind direction |       |       |       |       |       |       |       | Average wind speed | Mean wind direction | Wind direction std dev. | Direction sector for mean wind | Direction sector with highest frequency |
|-------------------------|------|----------|----------------|-------------------------------------|--|-------|-------|-------|-------|-------|-------|-------|--------------------|---------------------|-------------------------|--------------------------------|---|
|                         |      | mm       | m/s            | speed                               | 1                                      | 2     | 3     | 4     | 5     | 6     | 7     | 8     | m/s                | degrees             | degrees                 | wind                           | frequency                               |
| 09/25/99                | 330  | 0.254    | 2.2            | 1                                   | 0.411                                  | 0     | 0     | 0     | 0     | 0     | 0     | 0.588 | 1.4                | 331.5               | 15.0                    | 8                              | 8                                       |
| 17. 09/29/99            | 1600 | 0.762    | 8.2            | 5                                   | 0                                      | 0     | 0.022 | 0.144 | 0.633 | 0.166 | 0.033 | 0     | 4.3                | 179.3               | 30.6                    | 5                              | 5                                       |
| 09/29/99                | 1615 | 3.048    | 9.1            | 6                                   | 0                                      | 0.011 | 0.011 | 0.055 | 0.455 | 0.211 | 0.211 | 0.044 | 3.6                | 206.5               | 49.9                    | 6                              | 5                                       |
| 09/29/99                | 1630 | 0.254    | 4.9            | 5                                   | 0                                      | 0     | 0.011 | 0.111 | 0.821 | 0.055 | 0     | 0     | 3.2                | 171.7               | 17.4                    | 5                              | 5                                       |
| 09/29/99                | 1645 | 0.762    | 4.0            | 5                                   | 0                                      | 0     | 0     | 0.222 | 0.744 | 0.033 | 0     | 0     | 2.8                | 166.3               | 16.3                    | 5                              | 5                                       |
| 09/29/99                | 1700 | 0.254    | 4.4            | 5                                   | 0                                      | 0     | 0.022 | 0.189 | 0.61  | 0.1   | 0.078 | 0     | 2.3                | 176.8               | 34.0                    | 5                              | 5                                       |
| 09/29/99                | 1715 | 2.032    | 4.3            | 5                                   | 0.011                                  | 0.033 | 0.011 | 0.122 | 0.3   | 0.144 | 0.355 | 0.011 | 2.0                | 215.8               | 60.8                    | 6                              | 7                                       |
| 09/29/99                | 1730 | 0.762    | 4.4            | 5                                   | 0                                      | 0.011 | 0.033 | 0.122 | 0.411 | 0.078 | 0.277 | 0.067 | 2.3                | 202.5               | 58.8                    | 5                              | 5                                       |
| 09/29/99                | 1745 | 0.508    | 7.1            | 7                                   | 0.011                                  | 0.011 | 0.055 | 0.1   | 0.255 | 0.178 | 0.311 | 0.078 | 2.4                | 221.5               | 62.0                    | 6                              | 7                                       |
| 09/29/99                | 1800 | 0.508    | 4.8            | 4                                   | 0.022                                  | 0.011 | 0.022 | 0.122 | 0.355 | 0.255 | 0.211 | 0     | 2.2                | 205.4               | 52.7                    | 6                              | 5                                       |
| 09/29/99                | 1815 | 1.016    | 5.4            | 6                                   | 0.011                                  | 0     | 0.011 | 0.033 | 0.166 | 0.266 | 0.433 | 0.078 | 2.9                | 241.2               | 47.1                    | 6                              | 7                                       |
| 09/29/99                | 1830 | 0.762    | 7.8            | 7                                   | 0                                      | 0     | 0.022 | 0.011 | 0.089 | 0.277 | 0.566 | 0.033 | 3.5                | 247.9               | 35.0                    | 7                              | 7                                       |
| 09/29/99                | 1845 | 1.016    | 9.0            | 6                                   | 0.011                                  | 0.011 | 0     | 0.011 | 0.055 | 0.244 | 0.61  | 0.055 | 4.6                | 256.4               | 33.7                    | 7                              | 7                                       |
| 09/29/99                | 1900 | 1.270    | 10.2           | 7                                   | 0                                      | 0     | 0     | 0.011 | 0.011 | 0.178 | 0.688 | 0.111 | 5.3                | 266.0               | 26.7                    | 7                              | 7                                       |
| 09/29/99                | 1915 | 1.524    | 10.8           | 7                                   | 0                                      | 0     | 0     | 0     | 0     | 0.122 | 0.81  | 0.067 | 6.7                | 268.8               | 19.6                    | 7                              | 7                                       |
| 09/29/99                | 1930 | 0.508    | 7.1            | 7                                   | 0.011                                  | 0.011 | 0.011 | 0.022 | 0.022 | 0.133 | 0.699 | 0.089 | 3.6                | 262.4               | 35.3                    | 7                              | 7                                       |
| 09/29/99                | 1945 | 0.508    | 6.7            | 7                                   | 0.022                                  | 0.022 | 0.011 | 0.011 | 0.033 | 0.089 | 0.699 | 0.111 | 2.7                | 269.4               | 37.7                    | 7                              | 7                                       |
| 09/29/99                | 2015 | 0.508    | 16.2           | 7                                   | 0.022                                  | 0     | 0     | 0     | 0.011 | 0.055 | 0.677 | 0.233 | 5.1                | 278.8               | 24.0                    | 7                              | 7                                       |
| 09/29/99                | 2030 | 0.254    | 16.4           | 8                                   | 0.189                                  | 0.011 | 0     | 0     | 0     | 0.011 | 0.122 | 0.633 | 10.9               | 318.4               | 24.4                    | 8                              | 8                                       |
| 09/29/99                | 2045 | 0.254    | 14.0           | 8                                   | 0.1                                    | 0     | 0     | 0.011 | 0     | 0.022 | 0.1   | 0.721 | 8.3                | 317.9               | 27.1                    | 8                              | 8                                       |
| 09/29/99                | 2100 | 0.254    | 14.5           | 8                                   | 0.111                                  | 0.011 | 0     | 0     | 0     | 0.011 | 0.044 | 0.821 | 8.3                | 317.1               | 18.7                    | 8                              | 8                                       |

Table 4.1 Meteorological Data for Intervals with Rainfall

| Episode number and date | Time | Rainfall | Max wind speed | Direction sector for max wind speed | Eight-bin frequency for wind direction |       |       |       |       |       |       |       | Average wind speed | Mean wind direction | Wind direction std dev. | Direction sector for mean wind | Direction sector with highest frequency |
|-------------------------|------|----------|----------------|-------------------------------------|--|-------|-------|-------|-------|-------|-------|-------|--------------------|---------------------|-------------------------|--------------------------------|---|
|                         |      | mm       | m/s            | speed                               | 1                                      | 2     | 3     | 4     | 5     | 6     | 7     | 8     | m/s                | degrees             | degrees                 | wind                           | frequency                               |
| 09/29/99                | 2115 | 0.762    | 14.1           | 8                                   | 0.122                                  | 0.011 | 0     | 0     | 0.011 | 0.011 | 0.1   | 0.744 | 8.2                | 316.3               | 25.3                    | 8                              | 8                                       |
| 09/29/99                | 2130 | 0.508    | 9.8            | 8                                   | 0.078                                  | 0.011 | 0     | 0     | 0     | 0.011 | 0.189 | 0.699 | 6.5                | 309.4               | 24.3                    | 8                              | 8                                       |
| 09/29/99                | 2145 | 0.254    | 12.6           | 8                                   | 0.133                                  | 0     | 0     | 0     | 0     | 0     | 0.055 | 0.799 | 7.4                | 317.8               | 17.5                    | 8                              | 8                                       |
| 09/29/99                | 2200 | 0.762    | 13.2           | 8                                   | 0.155                                  | 0.011 | 0     | 0     | 0     | 0     | 0.044 | 0.744 | 7.3                | 323.5               | 20.5                    | 8                              | 8                                       |
| 09/29/99                | 2215 | 1.016    | 11.6           | 8                                   | 0.033                                  | 0     | 0     | 0     | 0     | 0     | 0.122 | 0.844 | 6.2                | 308.9               | 16.1                    | 8                              | 8                                       |
| 09/29/99                | 2230 | 0.254    | 9.9            | 1                                   | 0.111                                  | 0     | 0     | 0     | 0     | 0     | 0.155 | 0.733 | 5.7                | 312.8               | 22.1                    | 8                              | 8                                       |
| 09/29/99                | 2245 | 0.254    | 7.1            | 8                                   | 0.033                                  | 0     | 0     | 0     | 0     | 0     | 0.366 | 0.599 | 3.9                | 298.1               | 16.4                    | 8                              | 8                                       |
| 09/29/99                | 2300 | 0.508    | 8.2            | 7                                   | 0.044                                  | 0     | 0     | 0     | 0     | 0     | 0.4   | 0.555 | 3.8                | 302.0               | 21.6                    | 8                              | 8                                       |
| 09/29/99                | 2315 | 0.254    | 5.1            | 8                                   | 0.022                                  | 0     | 0     | 0     | 0     | 0     | 0.3   | 0.666 | 2.9                | 303.8               | 18.9                    | 8                              | 8                                       |
| 09/29/99                | 2330 | 0.508    | 3.3            | 8                                   | 0.067                                  | 0     | 0     | 0.011 | 0     | 0.011 | 0.377 | 0.511 | 1.9                | 299.1               | 29.4                    | 8                              | 8                                       |
| 09/29/99                | 2345 | 0.254    | 2.7            | 7                                   | 0.011                                  | 0.022 | 0.022 | 0.1   | 0.166 | 0.078 | 0.555 | 0.044 | 1.6                | 248.7               | 61.7                    | 7                              | 7                                       |
| 09/29/99                | 2400 | 0.508    | 2.6            | 5                                   | 0.022                                  | 0.022 | 0.033 | 0.133 | 0.155 | 0.166 | 0.411 | 0.055 | 1.6                | 234.2               | 63.8                    | 6                              | 7                                       |
| 09/30/99                | 15   | 1.016    | 4.7            | 7                                   | 0.011                                  | 0     | 0     | 0     | 0.044 | 0.044 | 0.788 | 0.111 | 2.4                | 272.9               | 25.6                    | 7                              | 7                                       |
| 09/30/99                | 30   | 0.762    | 6.5            | 7                                   | 0.022                                  | 0     | 0     | 0     | 0     | 0.011 | 0.622 | 0.333 | 3.9                | 285.7               | 20.2                    | 7                              | 7                                       |
| 09/30/99                | 45   | 0.508    | 12.8           | 8                                   | 0                                      | 0     | 0     | 0     | 0     | 0.044 | 0.755 | 0.2   | 7.6                | 277.9               | 19.1                    | 7                              | 7                                       |
| 09/30/99                | 115  | 0.254    | 14.8           | 7                                   | 0                                      | 0     | 0     | 0     | 0.011 | 0.011 | 0.544 | 0.433 | 8.5                | 287.8               | 19.0                    | 7                              | 7                                       |

**Table 4.2 Horizontal rain fluxes during period 7/24/99 - 9/30/99**

Note: The unit of data is ml.

| Rainfall Episode                | Fifth Floor |      |       |      |     |     |      |       |      |       |      |      | Sixteenth Floor |       |       |      | Total |
|---------------------------------|-------------|------|-------|------|-----|-----|------|-------|------|-------|------|------|-----------------|-------|-------|------|-------|
|                                 | 1           | 2    | 3     | 4    | 5   | 6   | 7    | 8     | 9    | 10    | 11   | 12   | 13              | 14    | 15    | 16   |       |
| 7/28/99(13:00)-7/29/99(6:00)    | 691         | 482  | >1000 | 645  | 272 | 297 | 574  | 443   | 729  | >1000 | 363  | 204  | *               | >1000 | 515   | 302  | >9500 |
| 8/1/99(8:00 - 13:00)            | 137         | 203  | 360   | 470  | 84  | 195 | 139  | 23    | 76   | 245   | 198  | 165  | 321             | 104   | 115   | 142  | 2977  |
| 8/8/99(3:00) - 8/10/99(8:00)    | 3           | 41   | 75    | 31   | 0   | 27  | 32   | 42    | 43   | 25    | 31   | 18   | 34              | 29    | 0     | 12   | 443   |
| 8/10/99(9:00) - 8/13/99(14:00)  | 0           | 5    | 0     | 0    | 2   | 1   | 15   | 2     | 6    | 31    | 3    | 0    | 1               | 12    | 0     | 0    | 78    |
| 8/13/99(14:00) -8/16/99(8:00)   | 67          | 74   | 254   | 702  | 35  | 234 | 46   | 76    | 82   | 166   | 124  | 76   | >1000           | >1000 | 46    | 98   | >4000 |
| 8/24/99(16:00) - 8/25/99(12:00) | 538         | 825  | 97    | 202  | 83  | 76  | 136  | >1000 | 490  | 521   | 899  | 528  | 212             | 142   | >1000 | 849  | >7600 |
| 8/25/99(12:00) - 8/26/99(11:00) | 107         | 129  | 56    | 95   | 27  | 5   | 13   | 184   | 101  | 100   | 54   | 16   | 48              | 58    | 24    | 14   | 1031  |
| 8/26/99(11:00) - 8/26/99(15:30) | 16          | 35   | 40    | 67   | 6   | 0   | 2    | 0     | 23   | 5     | 19   | 17   | 24              | 2     | 27    | 8    | 291   |
| 9/13/99(17:00) - 9/14/99(11:00) | 3           | 2    | 6     | 0    | 1   | 0   | 0    | 0     | 0    | 12    | 0    | 0    | 0               | 0     | 0     | 0    | 24    |
| 9/16/99(11:00) - (17:00)        | 0           | 0    | 58    | 0    | 0   | 0   | 11   | 19    | 15   | 32    | 0    | 0    | 0               | 46    | 0     | 0    | 181   |
| 9/20/99(11:00) - 9/21/99(9:00)  | 38          | 50   | 31    | 15   | 30  | 1   | 38   | 57    | 23   | 180   | 5    | 5    | 10              | 37    | 3     | 4    | 527   |
| 9/24/99(17:00) - 9/25/99(8:00)  | 0           | 10   | 50    | 30   | 4   | 0   | 10   | 0     | 10   | 6     | 10   | 15   | 50              | 40    | 9     | 0    | 244   |
| 9/29/99(15:00) - 9/30/99(1:15)  | 170         | 160  | 144   | 70   | 50  | 5   | 89   | 410   | 47   | 1740  | 175  | 51   | 293             | 143   | 121   | 80   | 3748  |
| <b>Total</b>                    | 1770        | 2016 | >2100 | 2327 | 594 | 841 | 1105 | >2200 | 1645 | >4000 | 1881 | 1095 | >3000           | >2600 | >1800 | 1509 |       |

\*: The bottle at location # 13 was missing. Considering the rain intensity and wind direction during this rain episode, it should have collected more than 1000 ml rainwater.

## **Appendix A**

### **Soiling Patterns on a Tall Limestone Buildings: Changes over Sixty Years**

**Soiling Patterns on a Tall Limestone Building:  
Changes over Sixty Years**

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## **Abstract**

Soiling of limestone caused by air pollution has been studied at the Cathedral of Learning on the University of Pittsburgh campus. The Cathedral was constructed in the 1930's during a period of heavy pollution in Pittsburgh, Pennsylvania. Archival photographs show that the building became soiled while it was still under construction. Reductions in air pollutant concentrations began in the late 1940's and 1950's and have continued to the present day. Concurrent with decreasing pollution, soiled areas of the stone have been slowly washed by rain, leaving a white, eroded surface. The patterns of white areas in archival photographs of the building are consistent with computer modeling of rain impingement showing greater wash off rates at higher elevations and on the corners of the building. Winds during rainstorms are predominantly from the quadrant SW to NW at this location, and wind speeds as well as rain intensities are greater when winds are from this quadrant compared with other quadrants; the sides of the building facing these directions are much less soiled than the opposing sides. Overall, these results suggest that rain washing of soiled areas on buildings occurs over a period of decades, in contrast to the process of soiling that occurs much more rapidly.

(Figure 7 can be used for ES&T News and Research Notes.)

## Introduction

Air pollutants in combination with rain are known to damage buildings made of calcareous stone (1,2). For example,  $\text{SO}_2$  can react with limestone and marble when the surface is moist (3-5), resulting in higher oxidation states of sulfur such as  $\text{SO}_4^{2-}$  and forming species such as gypsum ( $\text{CaSO}_4$ ) (6-8). Because gypsum occupies a greater volume than the original stone, the surface can crack and become pitted. The rough surface can then serve as a site for deposition of airborne particles that are responsible for discoloration. Gypsum is also more soluble in rainwater than the original stone, and thus the soiled surface can subsequently be washed away to leave a white, eroded area on the building. The rate at which the walls become soiled and the rate at which the soiled areas become white depend on pollutant deposition rates and the delivery of rain to the building walls. Although these processes have been known for some time, there have been no prior field studies on changes in soiling patterns on buildings over long periods of time.

## Background and Methods

We have investigated soiling on the Cathedral of Learning, a 42-story Indiana limestone building on the University of Pittsburgh campus in Pittsburgh, Pennsylvania. Building construction began in 1926, with the first stonework in 1929. Construction was completed in 1937 (9). The exterior has never been cleaned except by natural rainfall. In earlier work (10), we showed that airborne concentrations of gaseous  $\text{SO}_2$ , total  $\text{NO}_3^-$ , particulate  $\text{SO}_4^{2-}$ , and particulate elemental carbon were uniform with height between the 5<sup>th</sup> floor and the roof. Dry deposition rates of  $\text{SO}_2$  to perfect sink surfaces hung on the walls were only slightly greater on the 16th floor compared with the 5<sup>th</sup> floor. Soiled surfaces on the building were examined by scanning electron microscopy by McGee (11) and found to contain gypsum as well as flyash particles; white surfaces were found to contain

much less gypsum and flyash, implicating anthropogenic emissions as responsible for

the soiling. In recent work, we used a computer model for airflow around the building to estimate the delivery of raindrops to the building walls (12). The results of these studies suggest that pollutant deposition occurs on the entire exterior surface of the building, and that soiling patterns at specific locations on the walls are determined by competing processes of pollutant deposition and wash off by rain.

Here we extend the research on current soiling patterns at the Cathedral to consider changes in soiling over a period of several decades. We use historical air pollution records dating back to the 1930's, quantification of the amount of soiling on the Cathedral, and archival photographs to examine changes in soiling patterns since the Cathedral was constructed. We also consider the results of computer modeling of rain fluxes in comparison with archival and recent photographs.

## **Results and Discussion**

Figure 1 shows annual average concentrations over time for total suspended particles (TSP) and for SO<sub>2</sub> in Pittsburgh (13). The TSP data cover the years 1957-1997 and are for downtown, 3.2 kilometers west of the Cathedral. The SO<sub>2</sub> data are for downtown (1980-1998) and for the industrial area of Hazelwood, 3.3 kilometers south of the Cathedral (1978-1998). The data show steady decreases in concentration over time, mainly due to reductions in emissions from heavy industry and from mobile sources. Data on visibility reduction due to smoke from the early part of this century to the present suggest that average TSP levels were much greater than 200 µg/m<sup>3</sup> in the 1930's and 1940's, before regular TSP monitoring began (14). This is confirmed by archived data on dustfall in downtown Pittsburgh that show values decreasing from 30 tonnes/km<sup>2</sup> month in 1938-39 to 14 tonnes/km<sup>2</sup> month in the mid-1950's (14). The dustfall values have continued to

decrease and are now less than 5 tonnes/km<sup>2</sup> month.

The excessive pollution that existed in Pittsburgh in the 1930's implies that soiling began while the Cathedral was still under construction. This is confirmed by archival photographs. Figure 2 shows a set of photographs of the Forbes Avenue side of the Cathedral (facing SE), beginning with a picture taken in 1930. This early photo shows a white building without evidence of soiling. In contrast, the second photo from the late 1930's shows extensive soiling by this time. The arrows in these two photographs point out the same place on the left side of the building, at which location later photos in Figure 2 show a sharp boundary between white and soiled areas in the form of a "notch" of white. This notch enlarges downward over time, which we hypothesize is due to rain wash off. Comparing the photographs in Figure 2 shows that this notch extends four floors below the 25<sup>th</sup> floor patio in the late 1930's, 5 floors in 1962, between 5 and 6 floors in 1989, and 6 floors in 1995. Records from the National Weather Service in Pittsburgh indicate that the annual precipitation has been roughly constant during these years, so reductions in pollution must have shifted the balance between pollutant deposition and wash off by rain in favor of the latter.

Figure 3 compares enlarged photographs of a section of the Forbes Avenue face taken in 1930, 1934, 1950, and 1995. The first photo, taken from an enlargement of the 1930 photo in Figure 2, shows that the entire surface is unsoiled. By 1934, this area has become completely soiled. By 1950, the area has become partially white, as evidenced by the boundary between soiled and white areas. By 1995, the boundary has moved downward several meters. The same feature is barely visible in Figure 2 on the extreme right side of the photographs from 1962 through 1995. We hypothesize that the location of the boundary in the 1950 photo is the result of somewhat reduced pollutant levels by that time, such that rain wash off dominated over deposition of pollutants. Additional decreases in pollutants resulted in further wash off by rain, apparent in the

1995 photo. According to this hypothesis, the white areas in the 1950 and 1995 photos show stone that has become eroded by chemical conversion and rain wash off, in contrast to the white areas in the 1930 photo showing undamaged stone.

Figure 4 shows a photo of the Fifth Avenue side of the Cathedral taken in 1937. The photo is notable in that the main tower of the building, constructed in the early 1930's, is completely soiled. However, the stonework on the lowest four stories, which was installed later, is still white. It is clear that the time scale for soiling during the period of Pittsburgh's heavy pollution was only a few years at most.

We can gain insight into the competing processes of pollutant deposition and rain wash off by comparing soiling on different sides of the Cathedral and at different elevations. Figure 5 shows photographs of the four faces of the Cathedral as they appear in 1999. The Fifth Avenue and Bigelow Boulevard sides show very little soiling compared with the Forbes Avenue and Bellefield Avenue sides. The latter two building faces show less soiling near the top compared with lower elevations, suggesting more efficient wash off at greater heights. The patterns also suggest more efficient wash off near corners on the building, with greater amounts of soiling near the center of the walls.

We can quantify the amount of soiling as a function of height by considering discoloration of specific architectural features. One such feature is a decorative cross measuring 0.75 m x 0.56 m carved into the stone which appears at 226 locations on all four sides of the Cathedral. We have measured the percent of area soiled on each cross and have graphed the result as a function of height. For the Forbes and Bellefield Avenue sides, virtually all of the crosses are highly soiled,



even at the near the top of the building. For the Fifth Avenue and Bigelow Boulevard sides, the amount of soiling decreases with height. Figure 6 shows the result for Bigelow Boulevard. The average soiling ranges from 64% on the lower floors (8<sup>th</sup>–14<sup>th</sup>) to 34% on the 37<sup>th</sup> floor; patterns for the Fifth Avenue crosses are similar. It is of interest that Figure 5 indicates little soiling overall on these two sides, despite the occurrence of appreciable soiling on the irregular carved surfaces of the crosses. This suggests that carved stone surfaces, which include areas sheltered from raindrop impact and dripping rain, are less effectively washed over the years compared with broad, flat areas of the stone that comprise much of the wall surface area.. The abundance of soiling on the Forbes and Bellefield Avenue crosses is consistent with this hypothesis: the amounts of rain reaching the highest elevations is sufficient to wash off flat areas of stone, but not enough to wash the irregular surfaces of the crosses. The rain reaching the lower levels of the Forbes and Bellefield Avenue sides is insufficient to wash even the flat areas.

We can compare the soiling patterns discussed above with computer modeling of rain fluxes to the walls. The Cathedral has been modeled as a simple rectangular block, with each face divided into 15 sections of 10 m x 32 m. Wind speed, wind direction, and rainfall have been measured near the Cathedral over a seven-week period of generally typical meteorological conditions (April 29-June 18, 1998) and are used as model inputs. Two severe thunderstorms on June 2 that caused local flooding are considered outliers and have not been used in the computations shown here. The three-dimensional air flow field and associated raindrop trajectories have been modeled using a commercially available software package (FLUENT, Inc., Lebanon, N.H.), in which the Navier Stokes and continuity equations are solved numerically. Raindrop sizes are approximated from an exponential distribution (15). The simplified distribution consists of three raindrop sizes, 1.25, 2.5, and 5 mm, where the amounts of rain associated with each size depend

on measured rain intensity. The meteorological data are averaged over 15-minute intervals for computing the amount of rain striking each section of the building. There are a total of 207 time intervals where rain was recorded; wind and rain data for these intervals have been used in the calculations. The total rainfall for these intervals, normalized to one year, is 1210 mm/year. This compares with the average rainfall in Pittsburgh of approximately 1000 mm/year, with May and June each receiving about 10% of the annual rainfall. Details of the modeling have been reported elsewhere (12). Resultant rain fluxes normalized to one year are shown in Figure 7.

The figure shows that calculated rain fluxes to the Fifth Avenue and Bigelow Boulevard sides are much greater than those to the Forbes and Bellefield Avenue sides. This is consistent with the greater amounts of soiling in Figure 5 for the Forbes and Bellefield faces. On all four sides, the fluxes at the top are considerably greater than those at lower heights. Furthermore, the fluxes on the sides are greater than those in the center sections. These results are in agreement with the observations of less soiling near the top and at the corners of the building. Comparing model results with the meteorological input data shows that the greater rain fluxes on the Fifth and Bigelow sides are due in part to the large fraction of time (0.50) when the wind is from the quadrant SW through NW. Furthermore, the rain intensities are highest when the wind is from the SW, W, or NW (ave. 4.0 mm/hr) compared with all other directions (ave. 2.6 mm/hr), and the wind speed is greatest when the wind is from these three directions (ave. 2.5 m/s versus 1.7 m/s).

Although these conclusions are based on computations using only seven weeks of meteorological data, comparison with the wind speed, wind direction, and rain intensity data for the full year from the National Weather Service in Pittsburgh suggests that conditions during April-June 1998 were quite representative of year-round conditions. Thus we conclude that the combination of

frequent winds from SW through NW, greater wind speeds when the winds are from these directions, and greater rain intensities associated with these directions is believed to be mainly responsible for the soiling patterns on the Cathedral of Learning. The archival photographs suggest that soiling of the Cathedral occurred within a few years under highly polluted conditions. In contrast, the information presented here suggests that it has taken several decades for rainfall to remove much of the soiling and produce a white, eroded surface.

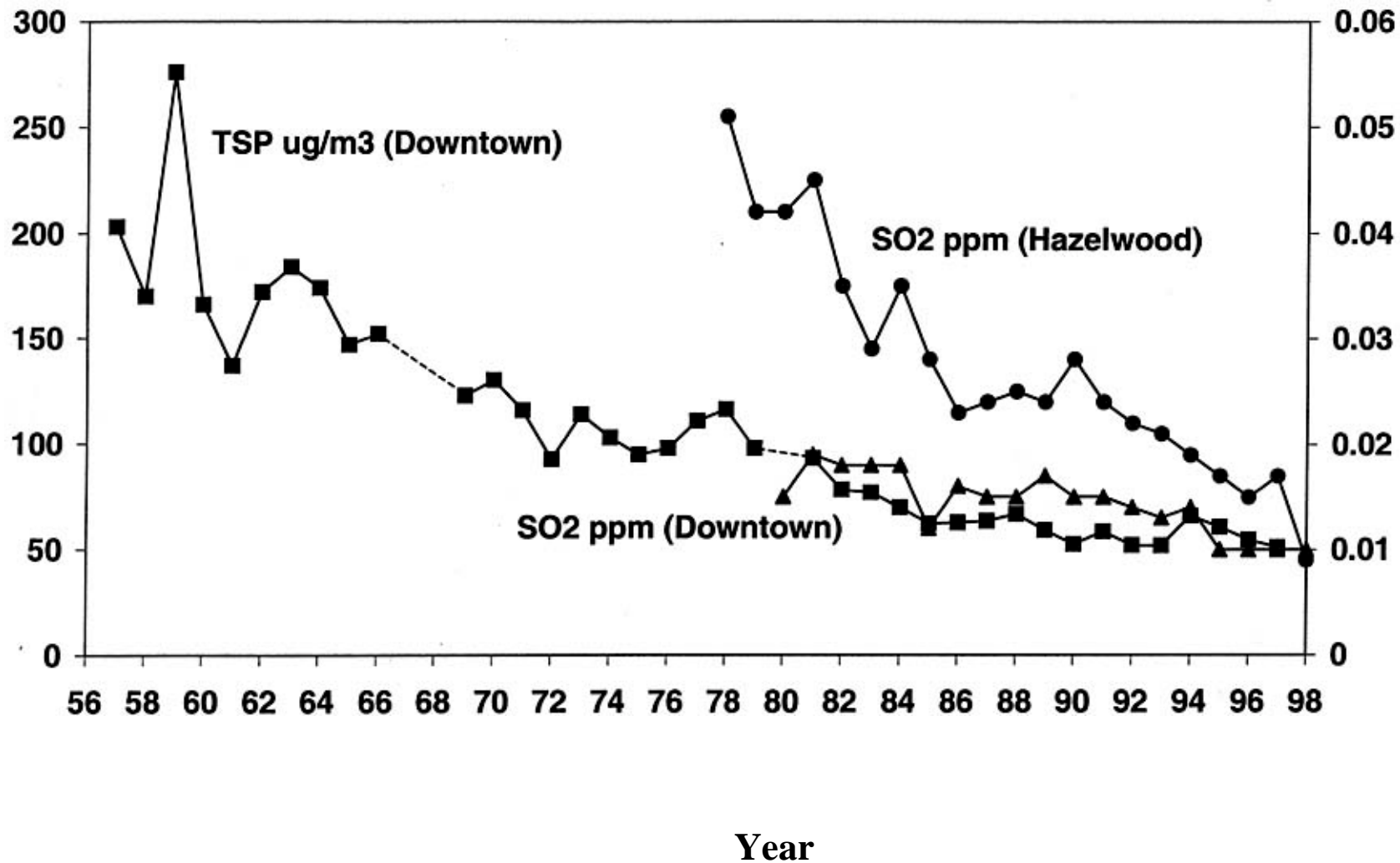
### **Acknowledgments**

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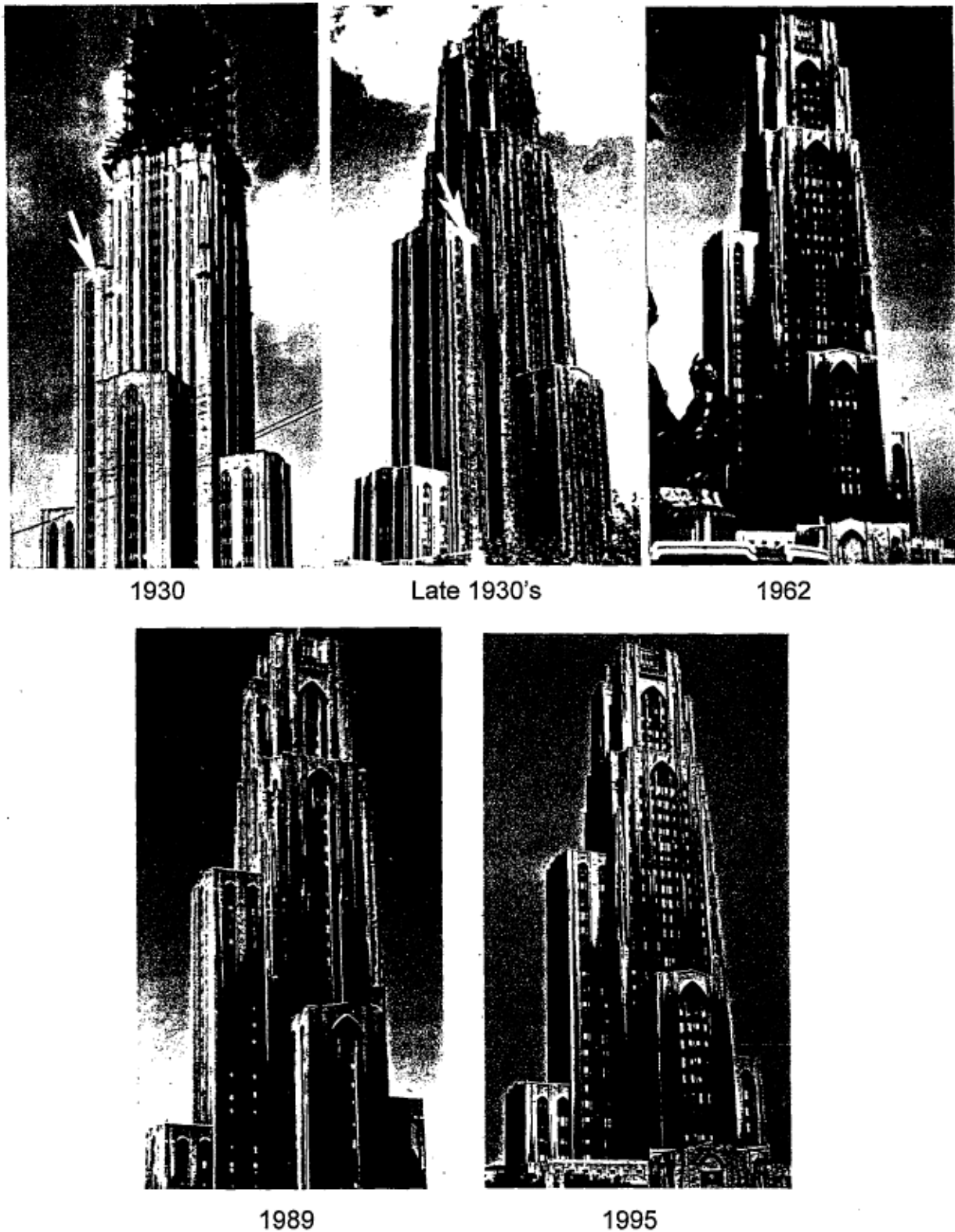
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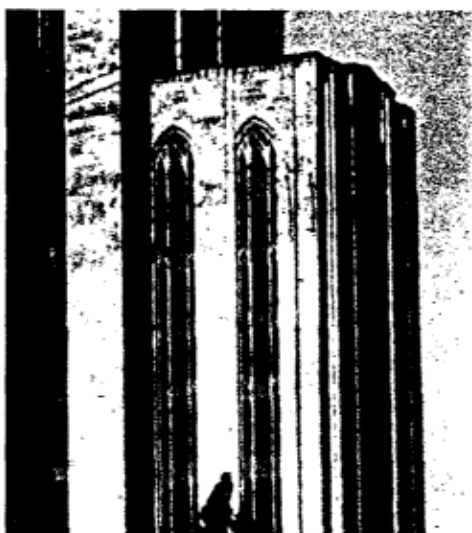
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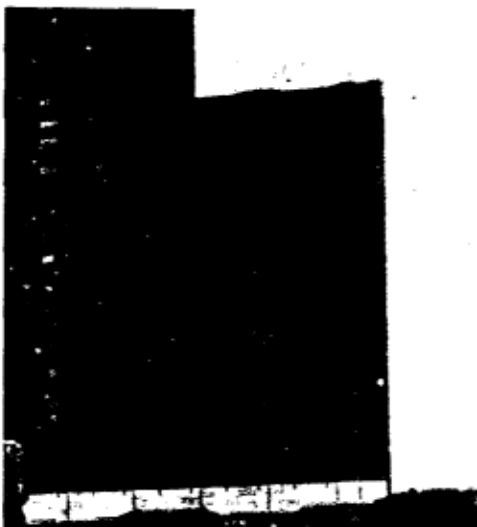
**Figure 1.** Annual arithmetic average concentrations of Total Suspended Particles (TSP) and SO<sub>2</sub> in Pittsburgh. The TSP measurements were made with high volume samplers at two downtown locations: the County Office Building (1957-1982) and Flag Plaza (1983-1997). The SO<sub>2</sub> measurements were made with continuous monitors at Flag Plaza downtown (1980-1998) and in the Hazelwood section of the city (1978-1998). These measurements were conducted as part of the National Air Sampling Network and the Air Quality Program of the Allegheny County Health Department. Reliable TSP data are not available for 1967, 1968 and 1980.



**Figure 2.** Archival photographs of the Forbes Avenue (SE facing) side of the Cathedral of Learning on the University of Pittsburgh campus. The arrows in the first two photos point to a wall section where the soiling pattern has changed with time. The wall below the arrow is unsoiled in 1930, but is mostly soiled by the late 1930's. The white "notch" at the top of the wall section enlarges downward over time as seen in the later photographs. Sources: 1930— University of Pittsburgh Archives; Late 1930's — Carnegie Library; 1962— University of Pittsburgh Archives; 1989— Herbert Ferguson, University of Pittsburgh Photography Services; 1995 — Justin Parkhurst.



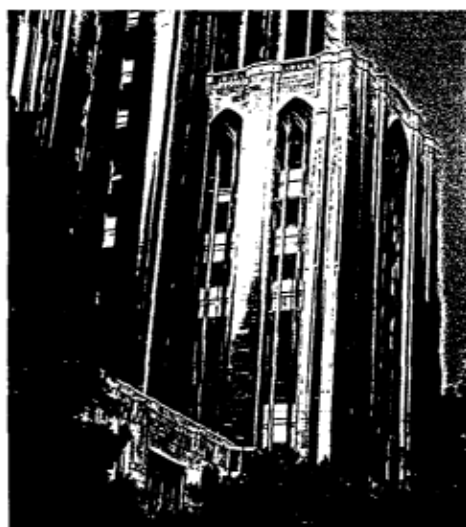
1930



1934



1950

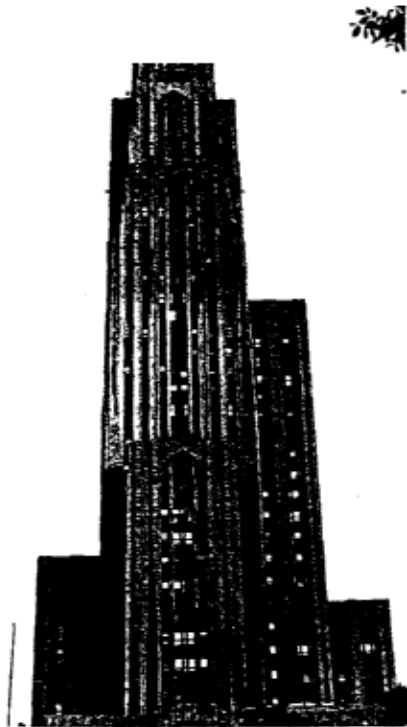


1995

**Figure 3.** Enlarged photographs showing a wall section on the right side of the Forbes Avenue face of the Cathedral. There is no visible soiling in 1930, but the wall is completely soiled by 1934. The 1950 and 1995 photos show increasing areas of white, hypothesized to be from rain wash off. Sources: 1930 and 1934 —University of Pittsburgh Archives; 1950 —Carnegie Library; 1995 — Justin Parkhurst.



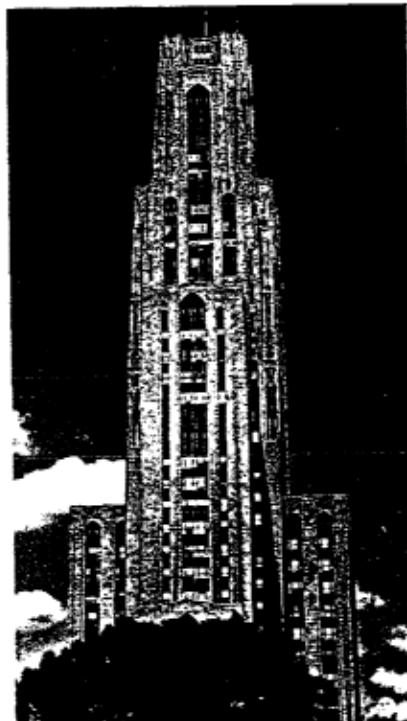
**Figure 4.** The Fifth Avenue side of the Cathedral in 1937. Source: University of Pittsburgh Archives.



Fifth Avenue side  
(facing NW)



Bellefield Avenue side  
(facing NE)

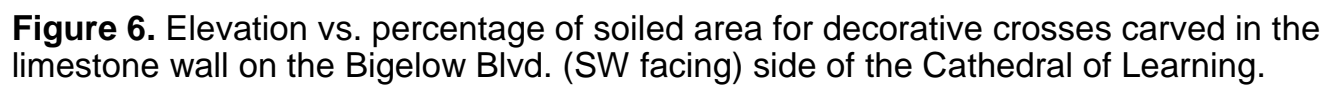


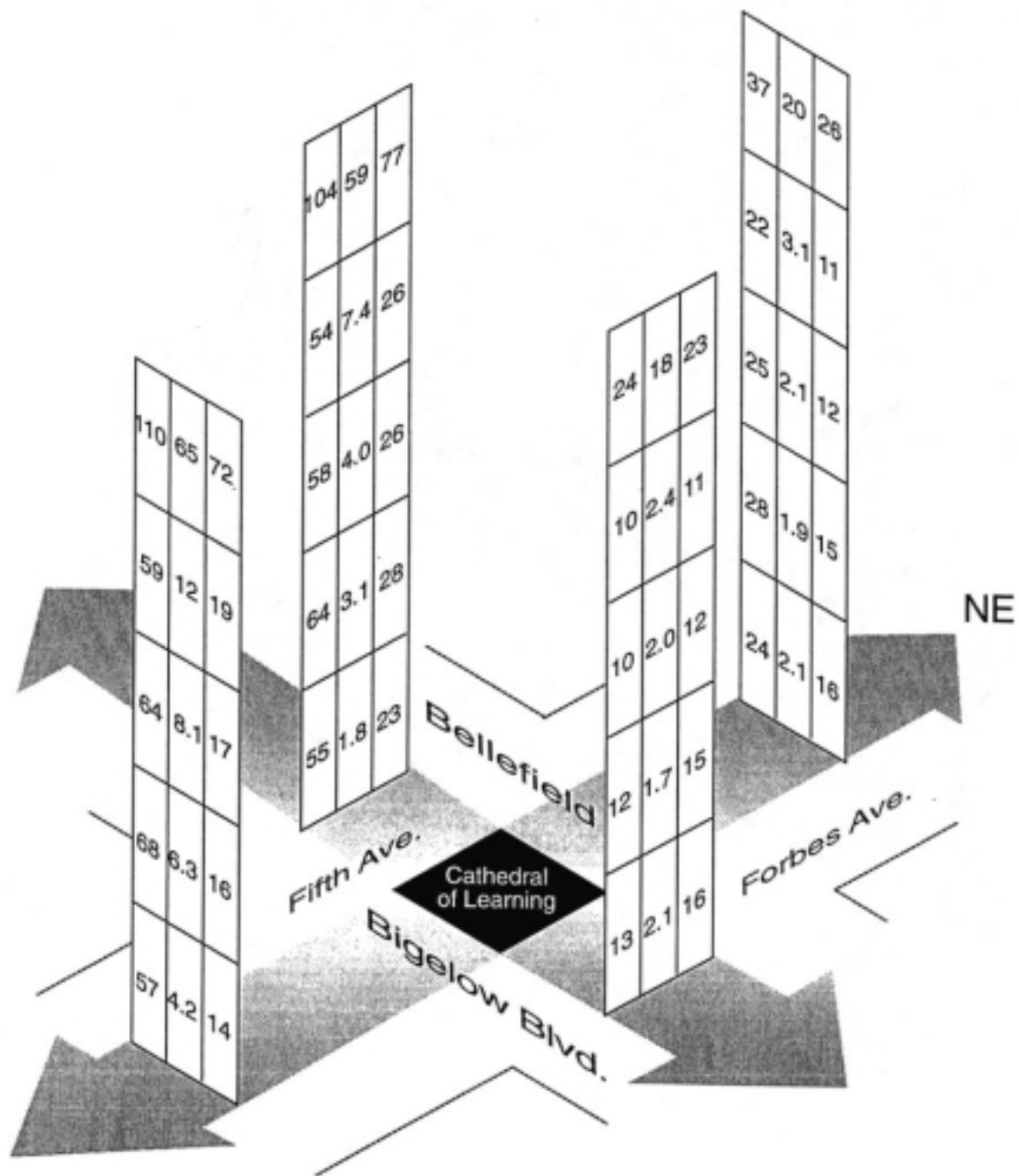
Bigelow Boulevard side  
(facing SW)



Forbes Avenue side  
(facing SE)

**Figure 5.** The four walls of the Cathedral of Learning in 1999. The Fifth and Bigelow faces are nearly entire white, while the Forbes and Bellefield faces have extensive soiling. Photographs by Wei Tang.





**Figure 7.** Computed rain fluxes in mm/year to the walls of a simple rectangular block with approximate dimensions of the Cathedral of Learning. Much more rain strikes the Fifth and Bigelow faces of the building compared with the Forbes and Bellefield faces.

## **Appendix B**

### **Changes of Soiling Patterns over Time on the Cathedral of Learning**

# CHANGES OF SOILING PATTERNS OVER TIME ON THE CATHEDRAL OF LEARNING

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Brimblecombe, editor, Imperial College Press, 1999

## 1. Introduction

Air pollution has been responsible for increasing the deterioration rate of structures made of limestone and marble. These calcareous stones are vulnerable to attack by several natural processes, including dissolution by rain, physical stresses such as freeze-thaw cycles, and microbial activity on the stone surface. Anthropogenic pollutant emissions may accelerate the natural erosion, resulting in pitting, cracking and discoloration.

One major cause of anthropogenic degradation is the formation of gypsum (Sherwood et al., 1990). This is the product of the reaction between calcium carbonate and acidic forms of sulfur, such as sulfuric acid. Gypsum occupies a greater volume than calcium carbonate, causing the stone to crack when gypsum forms. Furthermore, gypsum is more soluble in rain water than calcium carbonate, and thus rain may wash off the gypsum deposits, leaving pits in the stone. Gypsum is also more porous than the original stone, and can serve as an effective surface for the deposition of particles such as soot carbon. This can lead to discoloration of the stone, which is well-documented for limestone buildings.

In previous work (Etyemezian et al., 1999; Davidson et al., 1999), we hypothesized that soiling on a tall limestone building in Pittsburgh, Pennsylvania has been the result of two competing processes. The first is the deposition of pollutants on the stone, especially on sections of stone where gypsum has formed. The second process is wash off of soiled material by rain. Soiling patterns change when the relative rates of pollutant deposition and rain wash off vary over time.

In this paper, the changes in soiling patterns over time on the same limestone building have been studied based on archival photographs, analysis of soiling on architectural features, and computer modeling of horizontal rain flux. The results are used to support the hypothesis that soiling is determined mainly by the two competing processes.

## 2. Changes of soiling patterns

### 2.1 Background

The structure of interest is the Cathedral of Learning, a National Historic Landmark located in the densely populated Oakland area of Pittsburgh. This is a forty-two story Indiana limestone building on the University of Pittsburgh campus constructed between 1926 and 1937. Two sides of the Cathedral have extensive soiling, particularly on the lower half of the building. Since the time of construction, soiling has been evident as a result of numerous air pollutant sources within a few kilometers of the building. These include steel manufacturing plants that employ coke ovens and blast furnaces, a coal-burning steam heating plant, motor vehicle traffic, coal-burning railroads and riverboats, and a large number of domestic coal combustion sources such as home furnaces.

The Cathedral of Learning has attributes which lend itself to this type of study. Its location in an urban setting with detailed records of pollutant sources and concentrations allows the study of changes in soiling over time. Archival photographs of the Cathedral are available to permit comparisons between observed soiling and pollutant levels. The Cathedral is the tallest structure in the area, and thus prevailing wind and weather patterns will not be altered much due to surrounding structures, at least on the upper levels. There are certain architectural features repeated at many locations on the walls of the Cathedral, which can be used to quantify the amount of soiling at different elevations. The Cathedral has never been cleaned, except by natural rainfall. Finally, the Cathedral has historic and cultural value in its own right.

Since the time of construction of the Cathedral, Pittsburgh has experienced substantial changes in air pollution concentrations (Davidson, 1979). During the 1930's and 1940's, coal burning was responsible for the city's notorious smoke levels. In the late 1940's and throughout the 1950's, enforcement of smoke control ordinances reduced pollutant emissions. Stricter county ordinances in 1960 and 1970 as well as new federal regulations resulted in continued decreases in air pollution levels. Figure 1 presents annual average dustfall in the downtown area over an 85-year period. The continued decrease through recent decades is evident, especially the rapid decrease in dustfall during the late 1940's and early 1950's. Figure 2 shows airborne concentrations of total suspended particles (TSP) from 1957 to 1997 measured in downtown Pittsburgh with high volume samplers. A general decreasing trend is again observed.

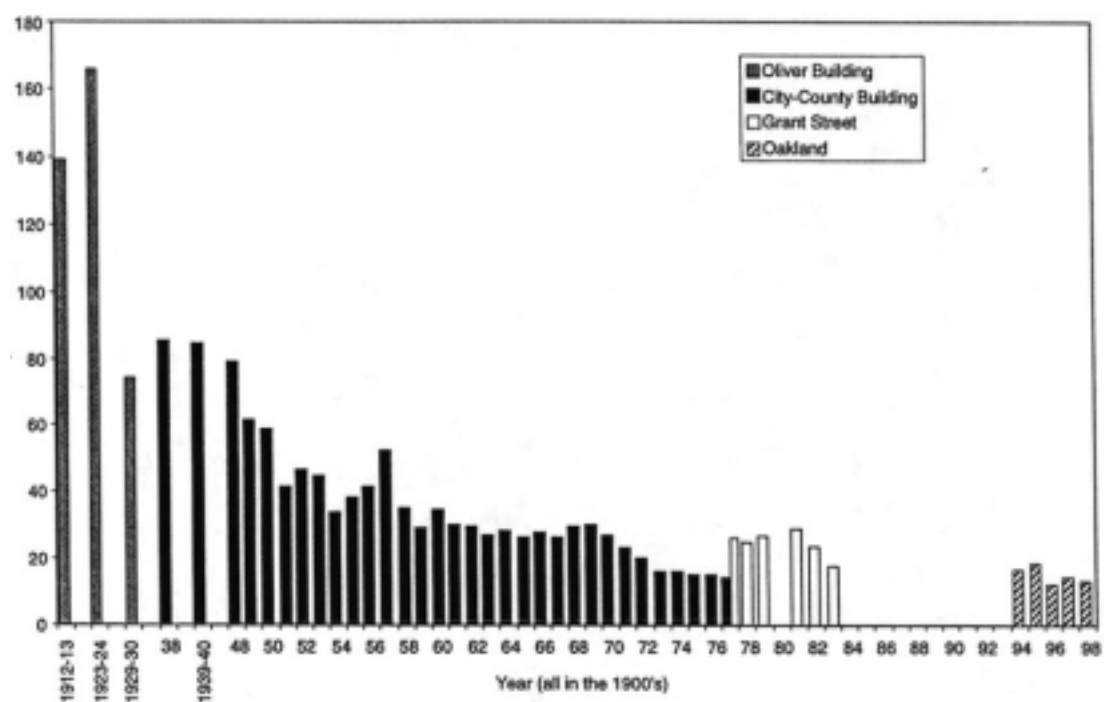
## *2.2 Changes in soiling patterns over time based on archival photographs*

We have studied how variations in pollutant concentrations shown in Figures 1 and 2 have affected soiling patterns on the Cathedral by examining photographs taken in previous years. For convenience, the faces of the Cathedral have been labeled with names of nearby streets. These are Bigelow Boulevard (SW side of the building), Fifth Avenue (NW side), Bellefield Avenue (NE side), and Forbes Avenue (SE side).

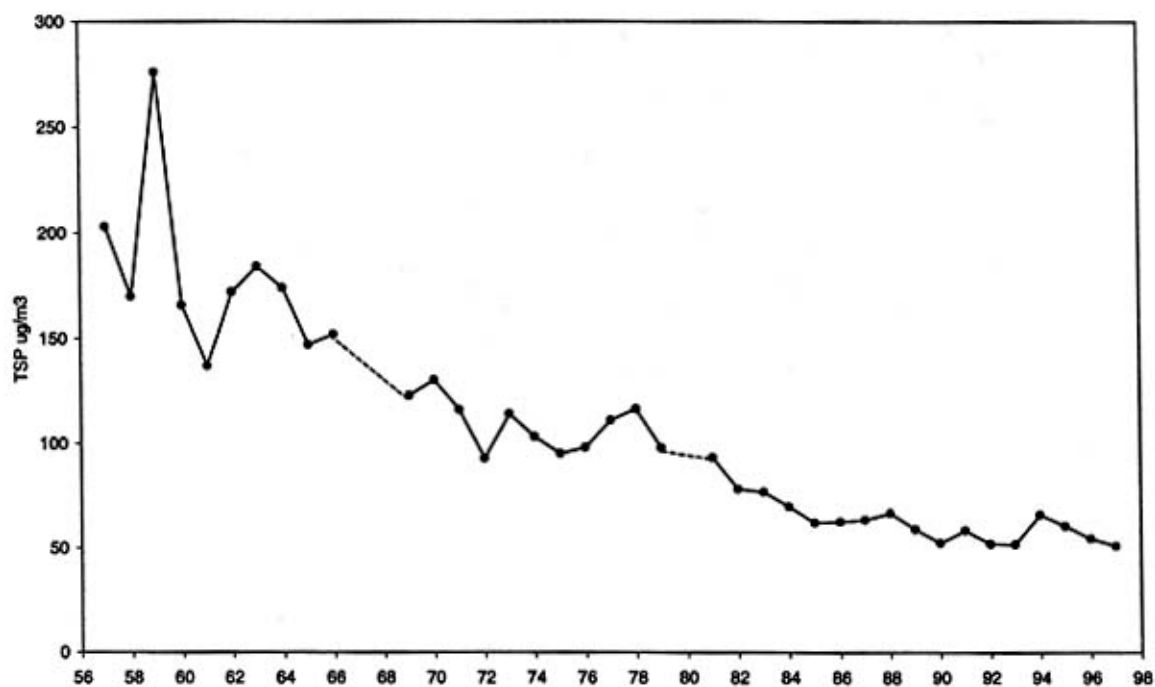
The first pair of photos in Figure 3 shows the Bigelow Boulevard side of the building. The photo from 1937 shows heavy soiling from approximately the 4<sup>th</sup> floor to the roof, except for the very top floor. An interesting feature of the building is that between 1929 and 1931, stonework was installed from the 4<sup>th</sup> floor up to the top. After that, work was stopped due to financial problems. It was not until the mid-1930's that stones for the lowest four floors were added and the top floor was reconstructed (Brown, 1987). Because of this fact, white stones at the top of the Cathedral (visible in the 1937 photo on the right side) have been a reference point to distinguish soiled sections from white ones. Using this reference point suggests that a significant amount of soiling occurred during 1931-1937. This coincides with heavy smoke in the 1930's throughout the region. In contrast, the photograph from 1995 shows that the entire Bigelow face of the building is almost free of soiling. Since no cleaning or renovation has been done since the completion of construction, it is likely that the reduction in soiling has been influenced by natural processes over time.

The photographs of the Forbes facade from the 1930's to 1999 in Figure 4 are useful for observing changes in soiling patterns over several time intervals. Generally, the decrease of soiling on this face is not as dramatic as that on Bigelow, but the heavy soiling in the early years and the decreasing amounts of soiling in more recent times are still apparent. The first photograph in the 1930's shows extensive soiling on the surface. In contrast, the later photographs show that the soiled area has been decreasing; since 1989, the top one-third of the building has been virtually free of soiling.

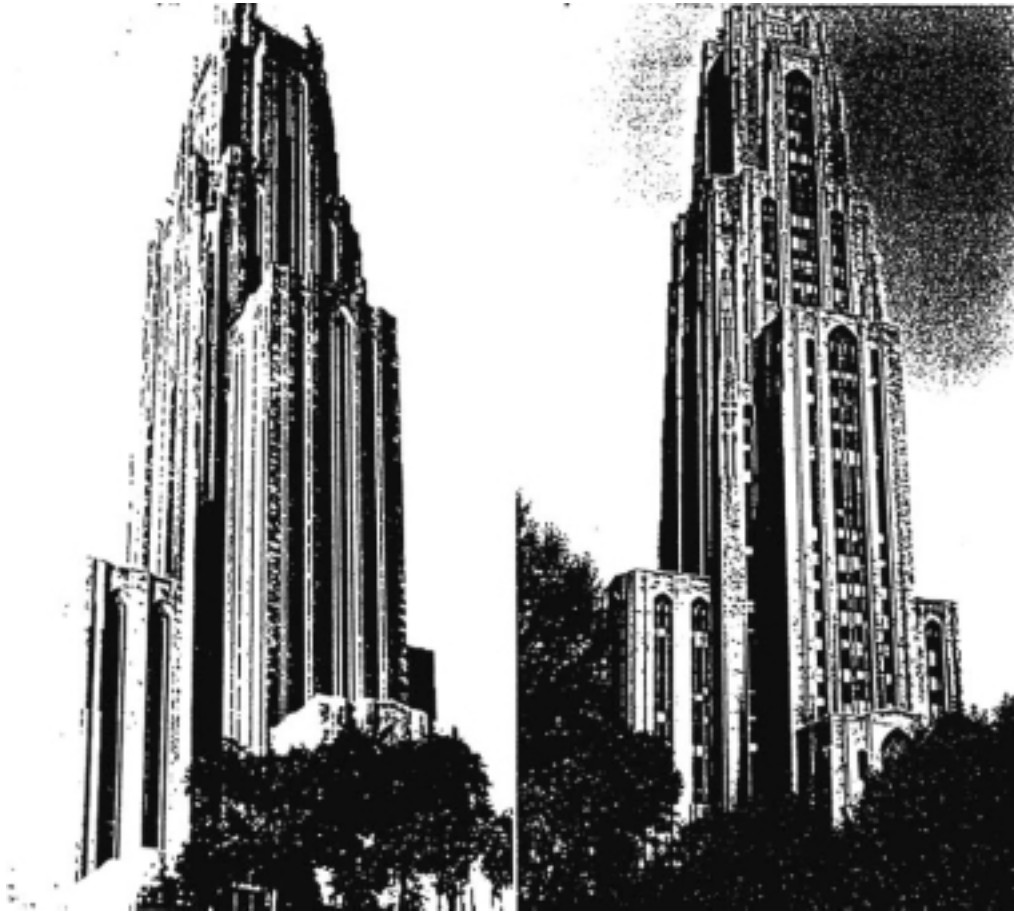
In addition to observations of the whole building, smaller scale changes on individual sections provide insight into the rain washing process. The location marked with an arrow on the first photograph shows a demarcation line between soiled and white areas on the left side of the Forbes Avenue face. This white region appears as a "notch" in the soiling, and has enlarged downward over time. In the photo from the 1930's, the bottom of the notch reaches the fourth window from the top of the section. By 1962, the notch has reached the middle of the fifth window. The photo from 1989 shows that the notch now reaches between the fifth and sixth windows. By 1995, the notch extends to the sixth window, and by 1999, the notch extends to the area between the sixth and seventh windows.



**Figure 1.** Annual average dustfall at four different sites in or near downtown Pittsburgh. No data are available for 1980 or for 1984-1993. Data are taken from archival and recent records at the Air Quality Program of the Allegheny County Health Department.



**Figure 2.** Annual arithmetic average concentrations of Total Suspended Particles in downtown Pittsburgh. The measurements were made with high volume samplers at the County Office Building (1957-1982) and Flag Plaza (1983-1997), as part of the National Air Sampling Network and the Air Quality Program of the Allegheny County Health Department. Reliable data are not available for 1967, 1968 and 1980. Reprinted with permission from American Chemical Society (Davidson et al., 1999).

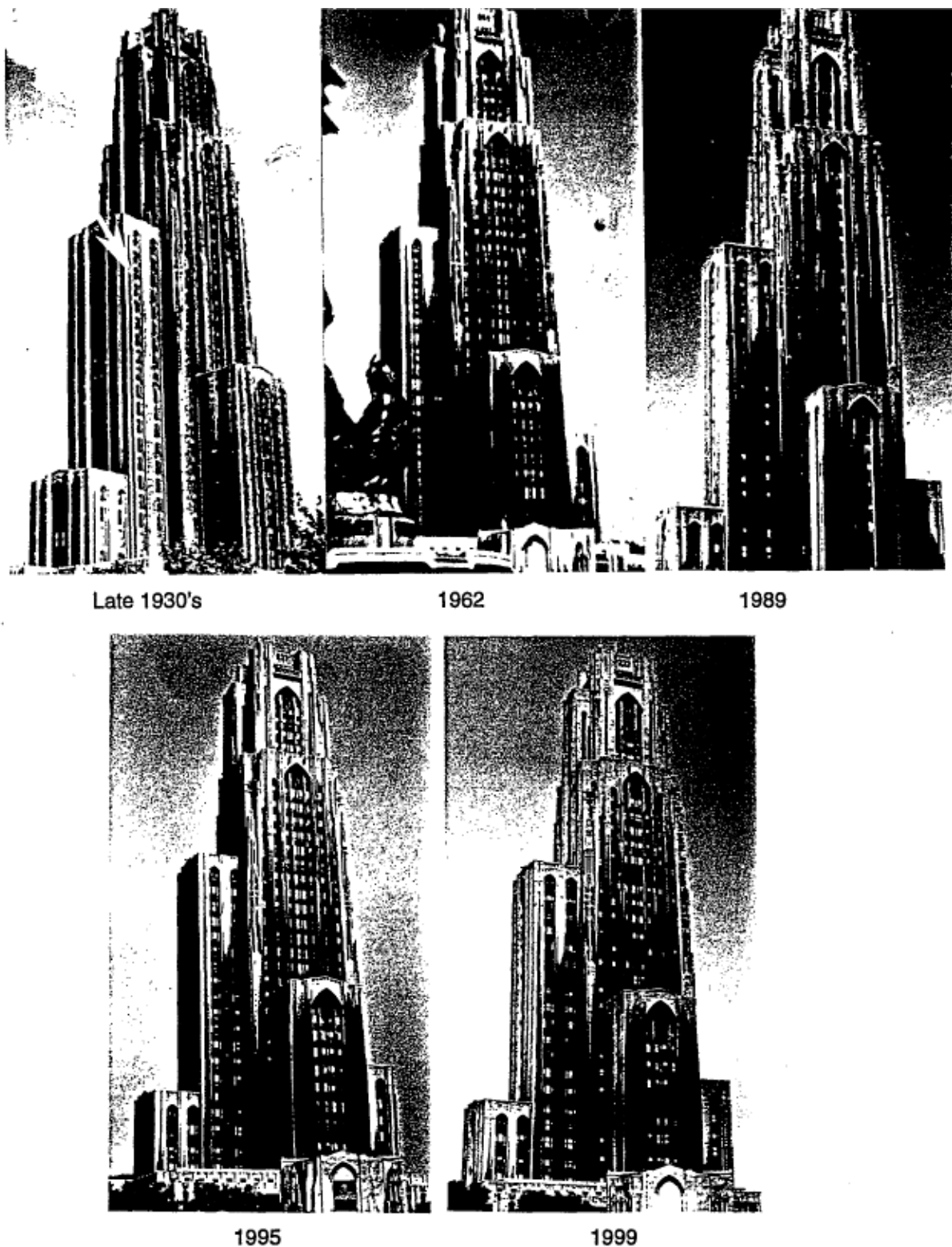


**1937**

**1995**

**Figure 3.** The Bigelow façade of the Cathedral of Learning in 1937 and 1995

Sources: 1937 — University of Pittsburgh Archives, 1995 — Cathedral of Learning Research Group, CMU.



**Figure 4.** Archival photographs of the Forbes Avenue (SE facing) side of the Cathedral of Learning on the University of Pittsburgh campus. Changes in soiling patterns, such as the white “notch” marked with an arrow in the first photograph, are apparent by comparison with the later photos. Sources: Late 1930’s -Carnegie Library, 1962 - University of Pittsburgh Archives, 1989 - Herbert Ferguson, University of Pittsburgh Photography Services, 1995 and 1999 - Cathedral of Learning Research Group, CMU. Reprinted with permission from American Chemical Society (Davidson et al., 1999).

These archival photographs suggest that the Cathedral of Learning has been washed by natural rainfall over time, which supports the hypothesis that soiling on building surfaces is the result of a competitive process between pollutant deposition and rain washoff. The overall trend of annual precipitation in Pittsburgh has been roughly constant over these decades (Etyemezian, et al., 1998). However, airborne concentrations of SO<sub>2</sub> and particles have decreased steadily over the same time period (Davidson, 1979). Thus, those areas of the facade that were soiled in the late 1930's have become white in recent years because the rate of removal of soiled material by rain washing is greater than the rate of soiling by pollutant deposition and chemical reaction. The opposite was true in the 1930's when air pollutant concentrations were considerably greater than at present.

The rates of washoff of soiling have been different on the four faces of the Cathedral. During the early years when pollutant deposition was dominant, soiling was almost uniform on each face, as shown by archival photographs from the 1930's. However, it is likely that the Bigelow face has received a greater rain flux than the Forbes face, as will be discussed below, so that the decrease of soiling on the Bigelow face is much more significant.

### *2.3 Analysis of soiling on architectural features*

To assess quantitatively the patterns of visible damage that have occurred on the Cathedral, the soiling patterns of repeated architectural features have been documented. One such repeated feature is a stone carving 0.56 m x 0.75 m in the shape of a large "X", which has been referred to as a "cross". There are 226 crosses scattered on all four faces of the Cathedral at different elevations. The soiling pattern on each cross has been sketched and scanned into a computer, and the percentage of discolored area has been determined (Gould et al., 1993; Lutz et al., 1994; Etyemezian et al., 1995).

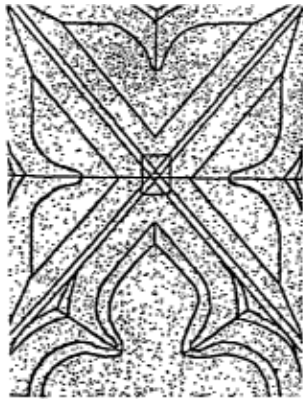
Figure 5 shows examples of four sketches with different percentages of soiled area. One sketch shows an ideal, unsoiled cross, while the other three sketches show soiled crosses on different floors on the Bigelow face of the building.

By examining data for all 226 crosses, we can find strong evidence for the hypothesis that pollutant deposition and rain washoff determine soiling patterns on the building. Most sharp edges of the carvings have been cleaned because they are exposed to raindrop impact and downward dripping of rainwater. In contrast, the sheltered areas below the edges show more soiling. Even for the crosses with a small percentage of soiled area, the lower center regions are black. The reason is that very little rainwater can flow over this area because it is sheltered by the edges. All crosses are at least 20% soiled, even in those areas where the flat sections of the wall are nearly entirely white.

Data from the crosses are presented in Figure 6 as plots of percentage of area soiled vs. elevation. From this figure, a negative correlation between percent area soiled and elevation by floor is observed, especially for the Bigelow Boulevard and Fifth Avenue faces where more soiled areas have been washed off. However, in the 1930's, a vertically uniform soiling pattern had been present for each face of the Cathedral as suggested by Figure 3 and other archival photographs. Furthermore, sampling of pollutants at the Cathedral has suggested that the distribution of airborne concentrations and deposition rates is roughly uniform with height at the building (Etyemezian et al., 1998). This implies that differences in the amounts of soiled area as a function of height observed today are the result of differences in rain flux rather than differences in pollutant levels.

### *2.4 Comparison of soiling patterns with modeling of rain impingement*

To explore further the role of rain washoff, the delivery of rain to the walls has been approximated by modeling the Cathedral as a simple prism. Each face has been divided into 15 sections (3 horizontal by 5 vertical sections), with each section having dimensions of 10 m x 32 m. The modeling results are presented in Figure 7, based on the original data from Etyemezian et al. (1999). The highest values of rain flux are on



0% soiled area



73% soiled area  
8<sup>th</sup> floor

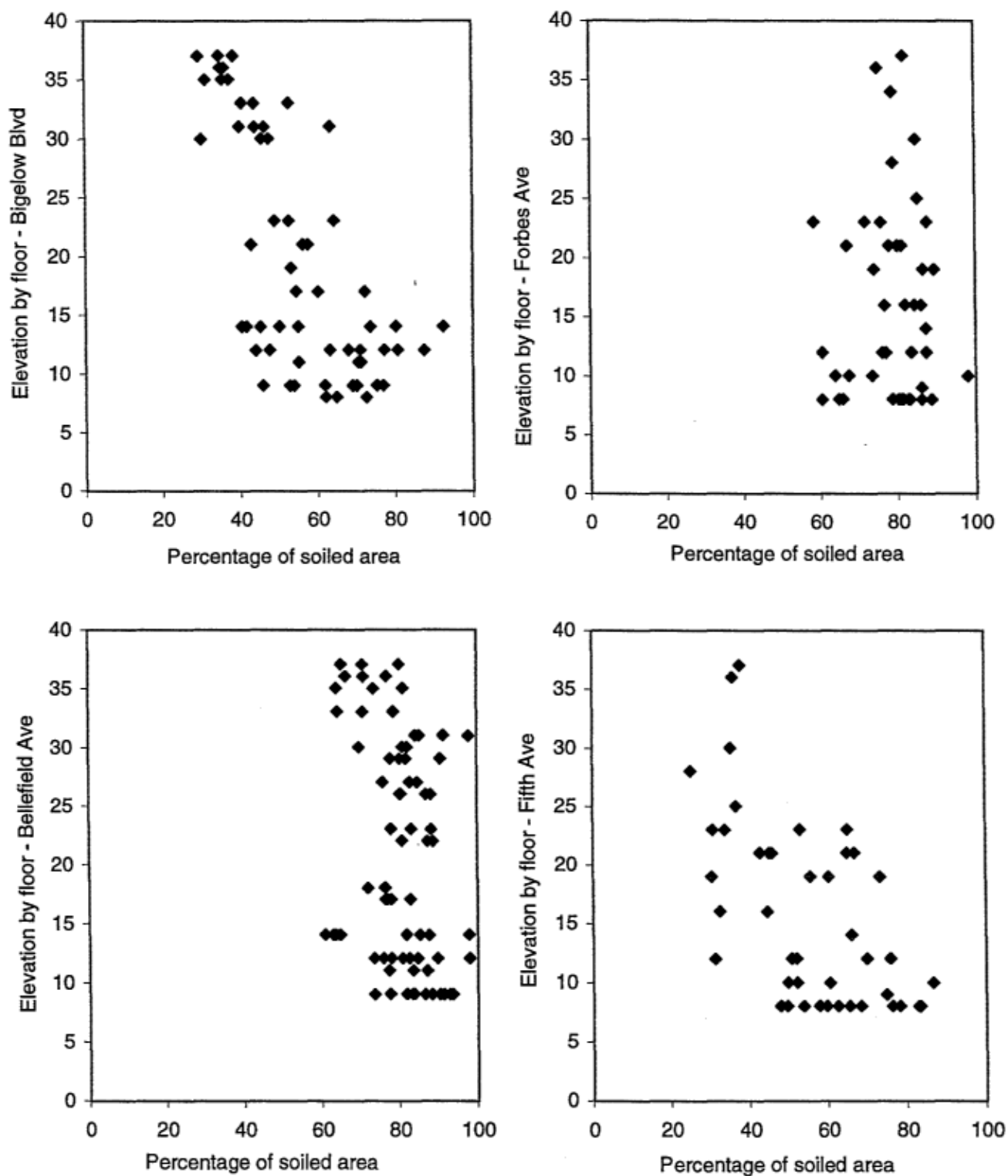


49% soiled area  
23<sup>rd</sup> floor

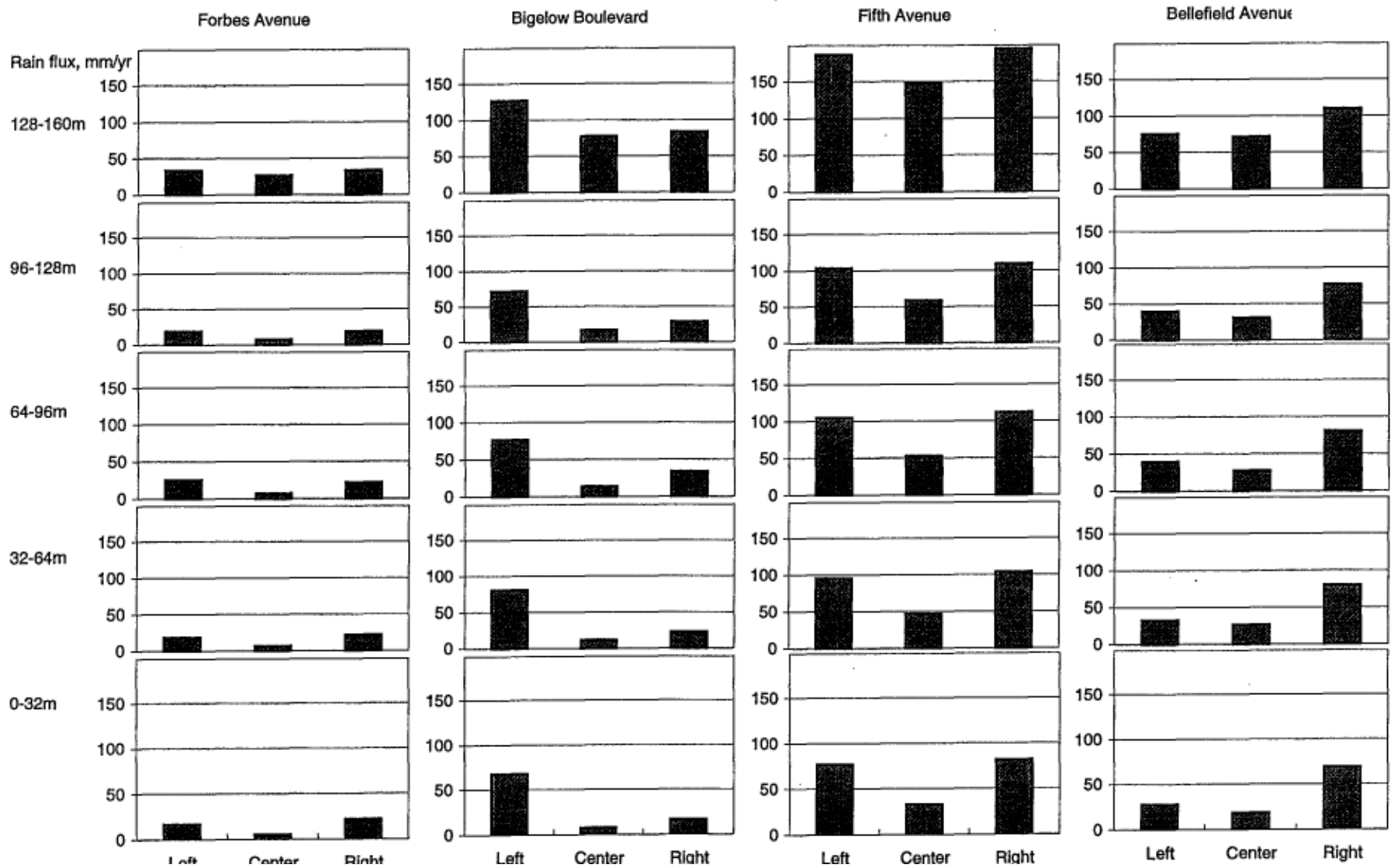


29% soiled area  
37<sup>th</sup> floor

**Figure 5.** Soiling patterns on crosses carved into the stone, a repeated architectural feature on the Cathedral of Learning. The upper left sketch shows an ideal, “unsoiled” cross, used as a blank in the computations of percent soiled area. The other three sketches are examples of soiled crosses taken from different floors on the Bigelow face of the building.



**Figure 6.** Elevation vs. percentage of soiled area for decorative crosses on the four faces of the Cathedral of Learning. Reprinted with permission from the American Chemical Society (Davidson et al., 1999).



**Figure 7.** Modeling Results of Rain Fluxes on Each Face of the Cathedral of Learning  
(Each face is divided into 3\*5=15 sections with dimension of 10m\*32m.)

the Fifth Avenue face while the lowest values are on the Forbes Avenue face; the Bigelow Boulevard and Bellefield Avenue faces have intermediate values. Despite differences in magnitude, patterns of rain delivery are similar for all four faces. The top sections of each face receive the greatest rain flux. Furthermore, the amount of rain delivered to the individual sections of a face increase with distance from the vertical centerline. In general, there is a reasonable, although not exact, correspondence between areas on the surface of the Cathedral that are white and sections of the simple prism in the model that receive the most rain. Thus the rain modeling results are consistent with both the observations of the crosses and with overall soiling patterns on the building.

### **3. Conclusions**

We hypothesize that soiling on calcareous stone buildings is the result of two competing processes: deposition of pollutants and washoff by rain. We have explored this hypothesis for the Cathedral of Learning, a 42 story limestone building constructed in the 1920's and 1930's in Pittsburgh, Pennsylvania. Several approaches have been used in this effort.

Comparison of archival with recent photographs shows that the Cathedral developed extensive soiling shortly after the completion of construction, and the soiling has decreased over the past several decades. This is consistent with decreasing trends in airborne pollutant concentrations and deposition rates since smoke control began in Pittsburgh in the late 1940's. Rainfall was roughly constant over the 60-year history of the building, and thus it is likely that the process of decrease of soiling began when pollutant levels had fallen sufficiently.

We have studied architectural features on the Cathedral to assess quantitatively the washoff of soiling on the building. By examining crosses carved into the stone at over 200 locations on the building, we have found that those carvings with the highest percentages of soiled area occur at the lowest elevations on the building. This is true despite airborne concentration and deposition data suggesting a roughly uniform distribution of pollutants with elevation at the building. The findings are consistent with the result of modeling raindrop impingement: the lower floors of the building surface receive a smaller rain flux than the higher floors. Overall, these results suggest that soiling on buildings in polluted areas is determined largely by both pollutant deposition and by delivery of rain to the building surface.

### **4. Acknowledgments**

We are grateful to the University of Pittsburgh for permission to conduct this research. We acknowledge the help of graduate students T. Gould, M. Lutz, and R. Strader as well as the help of the following undergraduate students in the work reported here: N. Barabas, B. Caster, J. Doan, B. Fontaine, D. Iorio, S. Jindal, S. Jutahkiti, S. Luckjiff, F. Molfetta, G. Mumpower, M. Nicholson, J. Parkhurst, K. Pinkston, and A. Puttaiah. The laboratory assistance of L. Cathwright is greatly appreciated, as is the general assistance of the Air Quality Program of the Allegheny County Health Department and the Facilities Management Department at the University of Pittsburgh. Valuable suggestions were provided by S. Pandis. This work was funded by the U.S. National Park Service Cooperative Agreements CA0424 19005 and 1443CA00196035.

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## **Appendix C**

### **Impingement of Rain Drops on a Tall Building**

## **Impingement of Rain Drops on a Tall Building**

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Keywords: soiling, buildings, driving rain, acid rain, CFD

9/14/99

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### **Abstract**

Soiling on the walls of limestone buildings can be washed off when the surface erodes due to rain impingement. In this study, the delivery of rain to the 42-story Cathedral of Learning in Pittsburgh, Pennsylvania, represented by a 30 m x 30 m x 160 m rectangular block, was modeled using the RNG K- $\epsilon$  model for turbulence and Lagrangian trajectory calculations for individual rain drops. Local Effect Factors (LEF) for the rectangular block compared well with earlier work in the literature. LEFs increased with wind speed, raindrop size, and height along the block.

Wind speed, direction, and rain intensity were measured continuously over a seven week period and provided input parameters for modeling rain fluxes to the Cathedral of Learning. Model results suggested that sections of the building receiving larger amounts of rain corresponded to white areas, indicating that rain fluxes have a significant effect on the soiling patterns. Intermediate wind speeds (2.5 and 5 m•s<sup>-1</sup>) resulted in high rain fluxes. Although less frequent, high wind speeds also resulted in high rain fluxes. Much of the rain was delivered to the block as 1.25 and 2.5 mm drops with 5mm drops having a smaller effect. Consideration of wind incidence angles other than 0° was shown to be important for future modeling efforts.

### **1. Introduction**

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Rain has been shown to be an important agent in determining the extent of calcareous stone erosion and the patterns of surface soiling on buildings (Amoroso and Fassina, 1983; Sherwood et al., 1990). For example, in polluted areas, delivery of acidic rain to the surface of a building can accelerate erosion. Even clean rain is believed to be responsible for some erosion of the surface (Mosotti and Eldeeb, 1994; Livingston, 1992). Particles that deposited on the surface may be removed as a consequence of rain washing. Thus, areas of a building that are exposed to driving rain are less likely to be soiled than those areas that are protected.

In this study, the flux of rain is estimated for several areas of the walls of the Cathedral of Learning (Figure 1) on the University of Pittsburgh campus. The building is 42 stories high and is made of Indiana limestone. Built during 1926-37, the walls are heavily soiled in some areas. This is attributed to pollutant emissions from mobile and stationary sources in the vicinity. The results of the modeling effort are presented in two parts. First, we examine the effect of meteorological conditions and raindrop sizes on the delivery of rain to the outside walls of a building shaped like a tall rectangular block. This is accomplished by computing the rain flux for several hypothetical values of wind speed, wind direction, and raindrop size. Second, we use meteorological data obtained near the Cathedral to estimate the total amount of rain that is delivered to the walls of the Cathedral. The spatial distribution of rain fluxes is compared with observed soiling patterns at the Cathedral.

Other work at the Cathedral of Learning has focused on changes in soiling patterns observed in archival photographs, and consideration of changes in air pollutant concentrations and dustfall since the Cathedral was constructed (Tang et al., 1999; Davidson et al., 2000). Etyemezian et al. (1998) measured airborne concentrations and deposition of various aerosol and gaseous chemical species near the walls of the Cathedral. It was determined that neither concentrations nor deposition varied greatly over the height of the building; the lack of gradients was attributed to a well-mixed atmosphere impinging on the Cathedral from upwind and possibly rapid vertical mixing in the immediate vicinity of the building. Soiling patterns on the building were hypothesized to be the result of variability in rain impingement on the walls. Testing this hypothesis is a focus of the current paper.

## **2. Methods**

Modeling of rain impingement on the walls of the Cathedral of Learning was accomplished in several steps. First, the air flow field around a rectangular block with the same approximate dimensions as the Cathedral was computed

numerically. Second, trajectories of individual rain drops, released above the block and subjected to the computed flow field, were calculated; the fate of each drop, i.e. whether it impacted on a surface of the block or the ground, was recorded. These two steps are partly based on earlier work by Choi (1993), allowing for comparison of results from this paper with his earlier work. Third, measurements of rain intensity, wind speed, and wind direction were obtained for a period of seven weeks at a location near the Cathedral. Combined with the results from the first two steps, this last step allowed for estimation of rain delivery to the four sides of the rectangular block used to represent the Cathedral of Learning.

### Air Flow

The shape of the Cathedral of Learning was approximated by a 30 m x 30 m x 160 m rectangular block ( $L \times W \times H$ ) for most model runs. This approximation helped reduce computational effort in two ways, namely by decreasing the detail of the geometry and also by rendering the flow field symmetrical about the plane that bisects the block along the primary direction of flow. The effect of nearby buildings was not considered since the Cathedral is much taller than any of the surrounding buildings. The reader is referred to Karagiozis et al. (1997) for an examination of the flow field and raindrop trajectories around buildings that exert an influence on one another.

The air flow field was modeled in three-dimensions using FLUENT, a commercially available computational fluid dynamics software package (FLUENT Inc, Lebanon, NH). The Reynolds-averaged Navier-Stokes and continuity equations were solved numerically to obtain the steady-state velocity field. Closure was achieved with the aid of the Re-Normalization Group K- $\epsilon$  (RNG) equations, where K is the turbulent kinetic energy and  $\epsilon$  is the turbulent kinetic energy dissipation. Application of Re-Normalization Group Theory to turbulence phenomena has been discussed elsewhere (Sulem et al., 1979; Giles, 1994). While largely similar to the standard K- $\epsilon$  model (Launder and Spalding, 1974; Rodi, 1980), the RNG model contains slightly different constants in the transport equations for K and  $\epsilon$  and an additional source term in the transport equation for  $\epsilon$ .

The accuracy of the RNG K- $\epsilon$  model was assessed by simulating the flow around a cube ( $L = W = H$ ) immersed in a boundary layer. This calculation was performed at wind incidence angles of  $0^\circ$  and  $45^\circ$ . A considerable body of information on these flow configurations, both from wind tunnel experiments (Castro and Robins, 1977; Ogawa et

al., 1983; Minson et al., 1995) and from other CFD efforts (Paterson and Apelt, 1989; Zhou and Stathopoulos, 1996; Murakami et al., 1996; Selvam, 1996), was available from the literature. In general, the major features of the flow were captured well by the RNG model. These included separation of the boundary layer at the ground near the upstream face, separation at the windward edges of the cube, development of a horizontal horseshoe vortex at ground level near the windward face, and the formation of vertical vortices on the leeward faces of the cube (Hosker, 1984).

The flow field around the rectangular block ("block" hereafter) was also computed at wind incidence angles of  $0^\circ$  and  $45^\circ$ . Since the air flow around the block is symmetric at these angles, it was possible to implement the CFD model for only half the physical domain of the flow field. For the  $0^\circ$  case, the computational domain extended 600 m the upwind direction, 670 m downwind of the block, 150 m from the plane of symmetry, and 540 m from the ground. The structured mesh, containing  $1.8 \times 10^5$  nodes, was constructed so that the density of nodes was highest near the block and ground. For flow at  $45^\circ$  to the block, the physical size of the computational domain was reduced because the block is more streamlined in this configuration. The domain extended 480 m upwind, 560 m downwind, 120 m from the plane of symmetry, and 480 m from the ground. Despite the reduction in the physical size of the domain, it was necessary to use more nodes in the  $45^\circ$  case ( $2.7 \times 10^5$ ) in order for the numerical solution to converge.

At the top boundary, the side boundary, and the plane of symmetry, components of velocity and gradients of all flow variables in the direction normal to the boundary were set to zero. For the ground and the surfaces of the block, standard wall functions (Rodi, 1980) were used to calculate the source terms for  $K$  and  $\epsilon$ . On the upwind boundary (inlet),  $K$ ,  $\epsilon$ , and the normal component of velocity were specified. The velocity was calculated according to a power law profile, i.e.,  $U(z)/U_r = (z/z_r)^n$ , where  $U(z)$  is the velocity in the direction normal to the upwind boundary,  $U_r$  is a reference velocity at a reference height of  $z_r$  and  $n$  is equal to 0.25; tangential components of the velocity were zero. Profiles for  $K$  and  $\epsilon$  at the upwind boundary were derived from the velocity profile (Patterson and Appelt, 1989) and were comparable to turbulence intensities on the order of a few percent. At the downwind boundary (exit), normal gradients of all flow variables except pressure were set to zero.

The numerical solution was considered to have converged when the normalized residuals for the U, V, and W velocity components, pressure, K, and  $\epsilon$  achieved a value of  $10^{-3}$  or lower. In the case of  $45^\circ$  wind incidence, it was not possible to reduce the normalized residuals for K and  $\epsilon$  below  $5 \times 10^{-3}$ , probably due to the assumption of steady flow (time-invariant). This assumption does not allow for adequate representation of temporal phenomena such as vortex shedding that may be inherent to the flow configuration (Castro and Robins, 1977).

#### Trajectories of Rain Drops

Trajectories of individual rain drops were calculated numerically according to:

$$M \frac{dU_i^P}{dt} = -F_{Di} - M\delta_{i3}g$$

$$F_{Di} = \frac{C_D \pi D_p^2 \rho}{4} (U_i - U_i^P) |U_i - U_i^P|$$

$M$  = rain drop mass

$U_i$  = air velocity in  $x_i$  direction

$U_i^P$  = drop velocity in  $x_i$  direction

$t$  = time

$F_{Di}$  = drag force in  $x_i$  direction

$g$  = gravitational constant

$\delta_{ij}$  = delta function;  $\delta_{ij} = 1$  if  $i = j$ ,  $\delta_{ij} = 0$  if  $i \neq j$ .

$C_D$  = coefficient of drag =  $f(\text{Re})$

$D_p$  = drop diameter

$\rho$  = density of air

$\nu$  = kinematic viscosity of air

$$\text{Re} = \text{sphere Reynolds number} = D_p \sqrt{\sum_1^3 (U_i - U_i^P)^2} / \nu$$

$C_D$  was obtained from empirical formulas for drag on a sphere (Morsi and Alexander, 1972). Trajectory calculations were performed for eight wind conditions, namely four values of wind speed ( $U_r = 1.25, 2.5, 5, \text{ and } 10 \text{ m}\cdot\text{s}^{-1}$  at  $z_r=30$  m) and two wind incidence angles ( $0^\circ$  and  $45^\circ$ ). For each of these conditions, trajectories of rain drops with diameters of 1.25, 2.5, and 5 mm were simulated. Rain drop evaporation, coalescence, or breakup were not considered, i.e. individual rain drop diameters were held constant at their initial values. In a limited number of cases, trajectories of 0.625 mm and 7.07 mm drops were also simulated. Results for those drop sizes, not presented here, were used for checking model consistency.

Approximately 4,000 trajectories were calculated for each flow condition and drop diameter. Drops were released at a fixed height of 240 m. Initial positions were varied over a horizontal area. This area was large enough to include all release positions that could result in impaction on the surface of the block. The initial vertical velocity was set at the terminal velocity while the initial horizontal velocity was set at the air velocity,  $U(z = 240 \text{ m})$ . In selected cases, the effect of turbulence on fluxes of rain to surfaces of the block was evaluated using a Random Walk model (e.g. Thomson, 1987; Dai et al., 1998). While not negligible for trajectories of individual drops, the effect of turbulence was small when fluxes of rain to large sections of the block were considered as in the present study. Air flow fields around buildings and resulting trajectories of raindrops are discussed at greater length by Choi (1993) and Karagiozis et al. (1997).

### Meteorological Data

A cup anemometer (Model 014A, Met One Instruments), wind vane (Model 024A, Met One Instruments), and tipping bucket rain gauge (Model 370, Micromet) were used to obtain meteorological data on the roof of Warner Hall on the Carnegie Mellon University campus over the period 4/29/98 to 6/18/98. Warner Hall is approximately one kilometer Ne of the Cathedral of Learning. A datalogger (Model CR21X, Campbell Scientific) recorded the average wind speed, eight-bin frequency count for wind direction ( $45^\circ$  per bin), and total rainfall amount for 15 minute measurement intervals. The maximum instantaneous wind speed during each interval and the corresponding wind direction were also recorded. These data, intended to represent meteorological conditions upwind of the Cathedral of Learning, provided input parameters for calculations of rain fluxes to the block surfaces. The seven week period included twenty-one days of rain. The overall rainfall during this period was equivalent to 1440

mm•yr<sup>-1</sup>. Sixteen percent of the rainfall over the period was contributed by two powerful thunderstorms on 6/2/98. The overall rainfall without those two thunderstorms was equivalent to 1210 mm•yr<sup>-1</sup>. The long-term rainfall rate for Pittsburgh is approximately 1000 mm•yr<sup>-1</sup>, with the months of May and June each contributing ten percent of the annual rainfall. The 21 days of rainfall contained 207 15-minute interval of rain with an average rainfall intensity of 3.3 mm•hr<sup>-1</sup> each (standard deviation = 5.7 mm•hr<sup>-1</sup>).

While wind conditions and rain intensity are represented by continuous distributions, model calculations of individual rain drop trajectories were performed at discrete conditions, e.g. wind speed = 5 m•s<sup>-1</sup>, wind incidence angle = 0°, and rain drop diameter = 1.25 mm. Thus, for compatibility between trajectory calculations and the measured parameters, it was necessary to place meteorological data in discrete categories. Measured values of wind speed were placed in one of four bins, equal in size (in logarithmic space) and centered at 1.25, 2.5, 5, and 10 m•s<sup>-1</sup>. Similarly, measured wind directions were placed in one of eight categories, each spanning 45°. The categories were chosen so that the wind would always approach the model block at angles of 0° or 45°.

For each 15 minute interval, the measured rain intensity was used to derive a discrete rain drop size distribution. The distribution consisted of only three drop sizes, having diameters of 1.25, 2.5, and 5 mm (Figure 2); these rain drop sizes allowed for comparison of results with the earlier work of Choi (1993) who used comparable values. The calculation was based on the exponential distribution proposed by Marshall and Palmer (1948):

$$n(D_p) = n_0 \exp(-XD_p)$$

$$n(D_p) \cdot dD_p = \text{number of drops per cm}^3 \text{ with diameter between } D_p \text{ and } D_p + dD_p$$

$$n_0 = 0.08 \text{ cm}^{-4}$$

$$X = 41R^{-0.21} \text{ cm}^{-1}$$

$$D_p = \text{rain drop diameter (cm)}$$

$$R = \text{rain intensity (mm} \cdot \text{hr}^{-1} \text{)}$$

Number concentrations for drops in the three size bins were multiplied by a correction factor so that the rain intensity due to drops with  $D_p = 1.25, 2.5, \text{ and } 5 \text{ mm}$  was equal to the rain intensity measured at Warner Hall. Note

that the instantaneous shape of the drop size distribution is expected to vary considerably. However, at long averaging times, the number concentration as a function of drop diameter may be adequately represented by an exponential distribution (Gori et al., 1988).

#### Rain Impingement Calculation

Each face of the block was divided into three vertical strips and five horizontal strips resulting in fifteen rectangular sections of equal size, 10 m x 32 m (Figure 1). This facilitated comparison of modeling results with soiling patterns at the Cathedral as well as comparison of results with the earlier work of Choi (1993). In order to assess the effects of individual parameters on the delivery of raindrops to each of the fifteen sections of the block, we adopted the Local Effect Factor (LEF) suggested by Choi (1993). For a given wind speed, incident flow orientation, and raindrop diameter ( $D_p$ ), the LEF for a vertical section of the block is equal to the ratio (expressed as a percentage) of the flux•m<sup>-2</sup> of rain drops of diameter  $D_p$  to that section divided by the flux•m<sup>-2</sup> of rain drops of diameter  $D_p$  to the ground far away from any flow obstructions.

Total fluxes of rain to the vertical walls of the Cathedral of Learning were estimated by combining meteorological data collected at Warner Hall with LEFs calculated for a discrete set of flow conditions and raindrop sizes. The amount of rain delivered to each section of the model block was calculated for every 15 minute interval (total of 207 intervals) that was associated with rainfall.

### **3. Results and Discussion**

#### Raindrop Delivery to the Block: Effect of Raindrop Diameter and Wind Conditions

LEFs are shown for four wind speeds and three rain drop diameters in Figure 3 for air flow perpendicular to the block (wind incidence angle = 0°). In general LEFs increase with increasing wind speed and raindrop diameter for any given section of the block face. This result is intuitive since inertial impaction of raindrops onto the building face is expected to increase at higher wind speeds and raindrop sizes. The spatial variation of LEFs across the block face is more complex.

LEFs increase with height along the block. This is to be expected since near the top of the block, raindrops still retain much of their initial vertical and horizontal momentum. At lower elevations, raindrops are moving slower in

the stream-wise direction due to both the shape of the incident wind profile (power law) and the disturbance in the air flow caused by the presence of the block. Thus, it is less likely that a raindrop will impact on the lower sections of the block than on the higher sections. Variations of LEFs across the rows of the block are interesting, especially for the case where the wind speed is  $10 \text{ m}\cdot\text{s}^{-1}$  (Figure 3d). For example, for  $D_p = 1.25 \text{ mm}$ , LEFs are lower at the center sections of the block (C1-C5) than they are to the outer sections (LS 1-5 and RS 1-5) in any given row. In contrast, for  $D_p = 2.5 \text{ mm}$  the center sections of the block have higher LEFs than the outer sections except at the top row where they are comparable. The same is true for  $D_p = 5 \text{ mm}$  except for the fourth row (LS4, C4, and RS4) where the center section is impacted by fewer raindrops than the side sections. These results are not an artifact of the resolution of the numerical model; changing the grid resolution for the CFD simulation or decreasing the time step in the Lagrangian trajectory calculations yields the same general behavior. More likely, these observations are due to the complex interaction of several phenomena including initial raindrop velocity, raindrop inertia, and the path that a raindrop follows. For example, raindrops with large diameters have higher terminal velocities than smaller drops. Consequently, the trajectories of large drops more closely approximate a vertical line than those of smaller drops. In order to impact the block, large drops have to follow a path that is closer to the block face than smaller drops. Therefore, these larger drops are more likely to interact with airflow immediately adjacent to the block, which is in an upward direction.

The results obtained in the present study for the block representing the Cathedral of Learning with relative dimensions of (1:1:5.3) compare favorably with those that were reported by Choi (1993) in Figure 4 for a building with relative dimensions of (1:1:4). Choi reported similar trends for changes in LEFs with changes in wind speed, raindrop size, and elevation along the building face. We note however, that values reported by Choi for raindrops with  $D_p = 1, 2, \text{ and } 5 \text{ mm}$  are generally higher than those presented here for  $D_p = 1.25, 2.5, \text{ and } 5 \text{ mm}$ . This discrepancy is especially noticeable for the cases where the wind speed is  $5 \text{ m}\cdot\text{s}^{-1}$  (Figures 3c and 4a). The two studies employ slightly different formulations of the CFD and Lagrangian trajectory models. In addition, we attribute much of the differences between the two sets of results to the different wind speeds and possibly different building heights (not reported by Choi).

Figure 5 shows LEFs for air flowing past the block at an oblique angle of  $45^\circ$ . Note that in this case, there are two windward faces that are expected to behave identically owing to the symmetry of the flow. Air is flowing from left

to right in this Figure, i.e. the left side of the block corresponds to the leading edge on the windward face. In general, for any given row, LEF values are highest to the upstream section (LS), lowest to the downstream section (RS), and intermediate at the center section (C). It is interesting that for wind speeds of 1.25, 2.5, and 5  $\text{m}\cdot\text{s}^{-1}$ , drops with  $D_p = 1.25$  mm have higher LEFs at sections LS 1-4 compared to drops with  $D_p = 2.5$  and 5 mm. At wind speeds of 10 m/s the highest LEFs for those sections are for  $D_p = 2.5$  mm, followed by  $D_p = 5$  mm. As in the case of flow normal to the block face, we attribute these counterintuitive results to the differences in terminal velocities of the raindrops. Smaller drops fall more slowly and therefore the angle of their trajectory with respect to the block face is sharper than larger drops whose trajectories are closer to being parallel to the block. Note that this effect is enhanced in the case of air flowing at 45°. As the wind speed is increased, inertial effects become more important and larger drops are more likely to impact on the block than follow the flow around the block. This contributes to the result that LEFs are higher for 2.5 mm drops than for 1.25 mm drops at 10  $\text{m}\cdot\text{s}^{-1}$ .

#### Raindrop Delivery to the Block: Results using April-June 1998 Meteorological Data

Figure 6 shows the fraction of time, the magnitude of the wind speed, and the average rain intensity associated with each wind direction during then rain events in the period April 29 to June 18, 1998. Note that the most common wind directions during rain events were W and SE, although both wind speed and rain intensity were greater during W winds. Figure 7 shows modeling results for rainwater fluxes to surfaces of the block using the meteorological data that are summarized in Figure 6. Sketches of the patterns of soiling at the Cathedral of Learning also appear in the Figure. The faces of the block and the corresponding sides of the Cathedral of Learning have been labeled with names of nearby streets. The meteorological data have been used with calculated LEFs to estimate the annual flux of rain to each section of the block. On 6/2/98 two unusually severe thunderstorms with very high winds (gusts  $>25 \text{ m}\cdot\text{s}^{-1}$ ) and intense rainfall swept through the Pittsburgh area. In Figure 7 numbers shown in black correspond to fluxes of rain excluding the 6/2/98 storms. The inclusion of the thunderstorms has profound effects on the magnitude of estimated rain fluxes, especially for the Fifth Avenue and Bellefield Avenue faces. A storm of such intensity, possibly related to El Niño, is a rare occurrence in Pittsburgh and its inclusion in the seven-week data set is likely to lead to biased estimates of rain fluxes to the Cathedral of Learning for other time periods; thus, the following discussion focuses on rain fluxes calculated without these storms. However, in Figures 7-10, rain fluxes calculated with these two storms are displayed in gray italics for completeness of data presentation.

There is reasonable, although not exact, correspondence between areas on the façade of the Cathedral of Learning that are white and sections of the block that receive the most rain. The Bigelow Boulevard and Fifth Avenue faces have high values of rain flux whereas the Forbes Avenue and Bellefield Avenue faces have lower values. This result qualitatively supports the hypothesis that soiling patterns at the Cathedral of Learning are determined to a large extent by delivery of rain to the building surfaces.

Despite differences in magnitude, patterns of rain delivery are similar for all four faces. For example, the amount of rain delivered to each face is highest at the top row (LS5, C5, and RS5) and is higher at the side sections (LS and RS) than the center sections (C). However, while fluxes to the left (LS) and right (RS) sections of the Forbes Avenue face are approximately equal, they are significantly higher on the left sides of the Bigelow Boulevard face than on the right side. The opposite is true for the Fifth and Bellefield Avenue faces.

Some of these observations are explained by the meteorology during the measurement period. Impingement of rain on the block surfaces is expected to be the greatest when the wind direction is favorable, wind speeds are high, and rainfall is intense. The high speeds of N, NW, W and SW winds combined with high rain intensities contribute to increased fluxes to the Fifth Avenue and Bigelow Boulevard faces as compared with Forbes and Bellefield Avenues. The low frequency of winds from the south result in lower fluxes to the right side of Bigelow Boulevard and the left side of Forbes Avenue. On the right side of Forbes Avenue and the left side of Bellefield Avenue, very low wind speeds and rain intensities also result in low fluxes of rain. This renders fluxes of rain to the Forbes Avenue face approximately symmetric with respect to the vertical centerline (C1-5), but higher rain intensities for N winds result in higher fluxes to the right side of the Bellefield Avenue face than the left side.

It is interesting that the right side of the Bigelow Boulevard face is white despite low values of rain fluxes. This may be the result of a large protrusion on the Bigelow Boulevard side that is not included in the block used in the model (Figures 1 and 7b). The fluxes of rain to the protrusion are likely to be much higher than they would be to the large block in the absence of the protrusion. It is also interesting that the vertical streak of soiling on the left side of the Cathedral is smaller than that on the right side. This is qualitatively consistent with the asymmetry of the estimated rain fluxes to the Bigelow Boulevard face.

The right side sections (RS1-4) of the Bellefield Avenue face are soiled even though the fluxes of rain to those sections are much higher than the fluxes of rain to some of the white, center sections (C1-C4) on the Fifth Avenue face. This may be the result of using a limited meteorological data set and a greatly simplified geometry. In addition, the block used in the numerical model is smooth whereas the Cathedral is a complex structure that has roughness on several scales. For example, the Cathedral has vertically oriented decorative features that span a large fraction of the building height (Figure 1). These structures can enhance the delivery of rain to sections of the Cathedral by capturing raindrops that would otherwise follow the air flow around the Cathedral. Furthermore, the model does not account for the runoff of water. Note that rain fluxes to the top rows (LS5, C5, and RS5) of the Fifth Avenue and the Bigelow Boulevard faces are quite high. If the stone at those sections becomes saturated, rainwater will run down the wall to lower sections, possibly eroding the stone as it falls. Thus, the extent of soiling on a particular section of the Cathedral depends not only on the rain fluxes to that particular section, but also on rain fluxes at higher elevations on the wall. However, we note that visual inspection of the limestone during light to moderate rainfall suggests that most of the water is absorbed into the stone close to the point of impact.

It is instructive to consider how different meteorological conditions contribute to the total fluxes of rain to sections of the Cathedral of Learning. In Figure 8, the fluxes of rain are categorized by wind speed. For brevity, results are only presented for Forbes Avenue (heavily soiled) and Fifth Avenue (primarily white). For both the Forbes and Fifth Avenue sides, most of the rain is delivered to the block at wind speeds of 2.5 and 5 m/s. While the highest LEFs are associated with a wind speed of 10 m/s (Figure 3), the occurrence of such wind speeds is somewhat rare. On the other hand, at wind speeds of 1.25 m/s, the LEFs are quite small. Thus, moderate LEFs combined with high frequencies of occurrence cause the intermediate wind speeds to be the greatest contributors to rain fluxes. However, by including the two large storms on 6/2/98 in the data set (numbers in gray italics), it can be seen that even a few occurrences of high winds during rainfall can have an appreciable effect on the total fluxes of rain to sections of the block. Consequently, much of the rain delivery to a building surface may result during gusts of wind which can be significantly larger in magnitude than the average wind speed for a given interval. For example, the average wind speeds for rainy 15 minute measurement intervals have a geometric mean of  $2.2 \text{ m}\cdot\text{s}^{-1}$  (geometric standard deviation,  $\sigma_g = 1.7$ ) while maximum wind speeds have a geometric mean of  $3.9 \text{ m}\cdot\text{s}^{-1}$  ( $\sigma_g = 1.7$ ). The data obtained at Wamer Hall also show a positive correlation between wind speed and rain intensity ( $\rho = 0.31$ ), further illustrating the importance of accurately accounting for rain events associated with high winds.

In Figure 9, the contributions to rain fluxes are categorized by raindrop diameter. According to the raindrop size distribution used in the present model (Figure 2), the rainfall amounts associated with 1.25, 2.5, and 5 mm drops are 578, 557, and 74 mm•year<sup>-1</sup>, respectively. LEFs are generally higher for 5mm drops than for 1.25 and 2.5 mm drops, but the low abundance of 5 mm drops results in their relatively small contribution to total rain fluxes. Compared to the other sizes, drops with a diameter of 1.25 mm deliver the least rain to the center sections of the faces while drops with a diameter of 5 mm contribute the least to the outer sections.

The effect of wind incidence angle on rain flux is illustrated by Figure 10. Note that the wind can be incident to a face at 45° from either the left or right side of that face. Significant amounts of rain are delivered to both the Forbes and the Fifth Avenue faces when the wind angle is 45°. The importance of considering oblique wind angles is illustrated by the data for Forbes Avenue, where more of the rain is associated with a wind angle of 45° than 0°, even though the former wind incidence angle occurs less frequently than the latter.

In addition to better approximating the geometry of a building, future modeling efforts should consider the temporal variations in the flow field. Here, the flow field was assumed to be at steady-state with respect to the Reynolds averaged Navier Stokes, K, and  $\epsilon$  equations, although this is likely to be far from actuality for a building in an outdoor environment. Furthermore, even when upstream flow conditions are invariant with time, there may be time-dependent phenomena on the building scale. Such phenomena, occurring primarily at oblique wind incidence angles, include sudden shifts in the location of the stagnation point on the windward side of the building and vortex shedding on the leeward side of the building (Castro and Robins, 1977; Hosker, 1984). This effect is not accounted for in the present model.

#### 4. Conclusions

A numerical model was used to investigate rain impingement on a tall limestone building and the influence of rain on soiling patterns. The RNG K- $\epsilon$  model was used to compute the steady-state air flow field around a 30m x 30m x 160m rectangular block, representing the Cathedral of Learning in Pittsburgh, Pennsylvania for several wind conditions. These included four wind speeds - 1.25, 2.5, 5, and 10 m•s<sup>-1</sup> - and two wind incidence angles - 0° and

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## List of Figures

**Figure 1.** a. Photograph showing Fifth Avenue side of Cathedral of Learning © 1984, Janosky Studios, Pittsburgh, Pennsylvania. Dashed outline is the part of the Cathedral that is represented by the rectangular block, and b. Division of block face into fifteen equal sections.

**Figure 2.** Discrete size distribution and theoretical Marshall-Palmer Distribution for  $R = 2, 10, \text{ and } 50 \text{ mm} \cdot \text{hr}^{-1}$ .  $D_p$  is in  $\text{m} \cdot \text{m}$ ;  $n(D_p)$  is in  $\text{cm}^{-4}$ .

**Figure 3.** Local Effect Factors (expressed as percentages) for rectangular block with dimensions of  $30\text{m} \times 30\text{m} \times 160\text{m}$  when the wind is perpendicular to block face ( $0^\circ$  incidence angle) for raindrops with  $D_p = 1.25, 2.5, \text{ and } 5 \text{ mm}$ . a. Wind speed =  $1.25 \text{ m} \cdot \text{s}^{-1}$ , b. Wind speed =  $2.5 \text{ m} \cdot \text{s}^{-1}$ , c. Wind speed =  $5 \text{ m} \cdot \text{s}^{-1}$ , d. Wind speed =  $10 \text{ m} \cdot \text{s}^{-1}$ .

**Figure 4.** Local Effect Factors (expressed as percentages) reported by Choi (1993) for rectangular block with relative dimensions of 1: 1: 4 for wind blowing perpendicular to block face ( $0^\circ$  incidence angle) for raindrops with  $D_p = 1, 2, \text{ and } 5 \text{ mm}$ . a. wind Speed =  $10 \text{ m} \cdot \text{s}^{-1}$  at 250 m (equivalent to  $5.8 \text{ m} \cdot \text{s}^{-1}$  at 30 m for comparison with Figure 3), and b. wind speed =  $20 \text{ m} \cdot \text{s}^{-1}$  (equivalent to  $11.6 \text{ m} \cdot \text{s}^{-1}$  at 30 m for comparison with Figure 3).

**Figure 5.** Local Effect Factors (expressed as percentages) for rectangular block with dimensions of  $30\text{m} \times 30\text{m} \times 160\text{m}$  when the wind is oblique to block face ( $45^\circ$  incidence angle) for raindrops with  $D_p = 1.25, 2.5, \text{ and } 5 \text{ mm}$ . The left edge of the block face represents the leading edge. a. Wind speed =  $1.25 \text{ m} \cdot \text{s}^{-1}$ , b. Wind speed =  $2.5 \text{ m} \cdot \text{s}^{-1}$ , c. Wind speed =  $5 \text{ m} \cdot \text{s}^{-1}$ , d. Wind speed =  $10 \text{ m} \cdot \text{s}^{-1}$ .

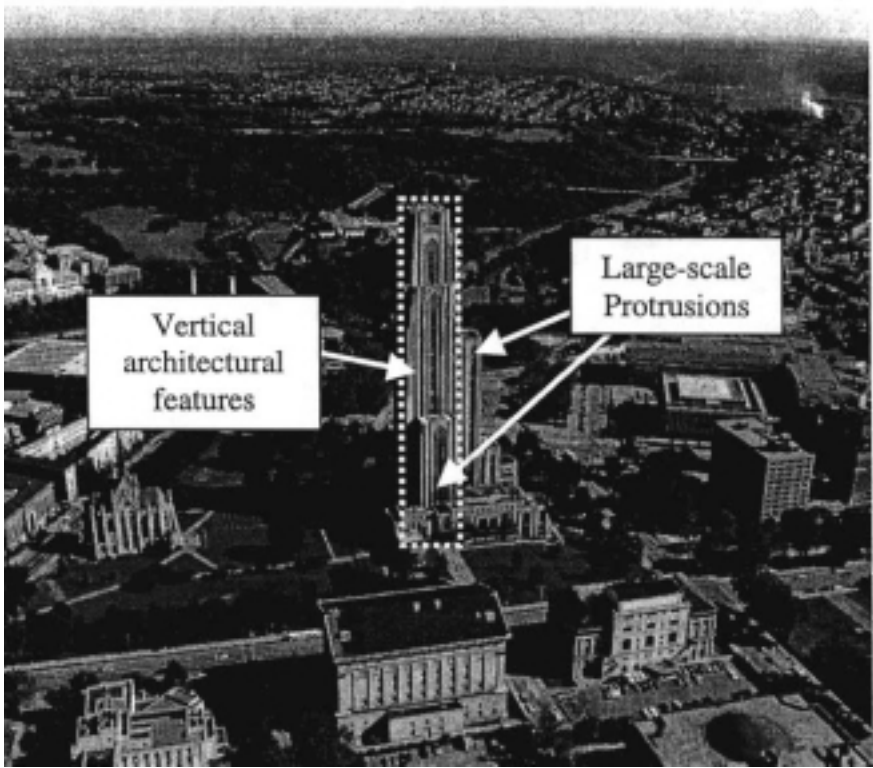
**Figure 6.** Meteorological conditions during rainy periods for 4/29/98 - 6/18/98.

**Figure 7.** Rain fluxes ( $\text{mm} \cdot \text{year}^{-1}$ ) to sections of rectangular block during 4/29/98 to 6/18/98, shown with soiling patterns at the Cathedral of Learning. Numbers in gray italics are for a data set that includes two large thunderstorms on 6/2/98. The average rainfall intensity over the same period was  $1210 \text{ mm} \cdot \text{year}^{-1}$  ( $1440 \text{ mm} \cdot \text{year}^{-1}$  including 6/2/98 storms).

**Figure 8.** Rain Fluxes ( $\text{mm} \cdot \text{year}^{-1}$ ) to sections of the rectangular block by wind speed. a. Forbes Avenue, and b. Fifth Avenue. Numbers in gray italics are for data set that includes two large thunderstorms on 6/2/98.

**Figure 9.** Rain Fluxes ( $\text{mm} \cdot \text{year}^{-1}$ ) to sections of the rectangular block by raindrop diameter. a. Forbes Avenue, and b. Fifth Avenue. Numbers in gray italics are for data set that includes two large thunderstorms on 6/2/98.

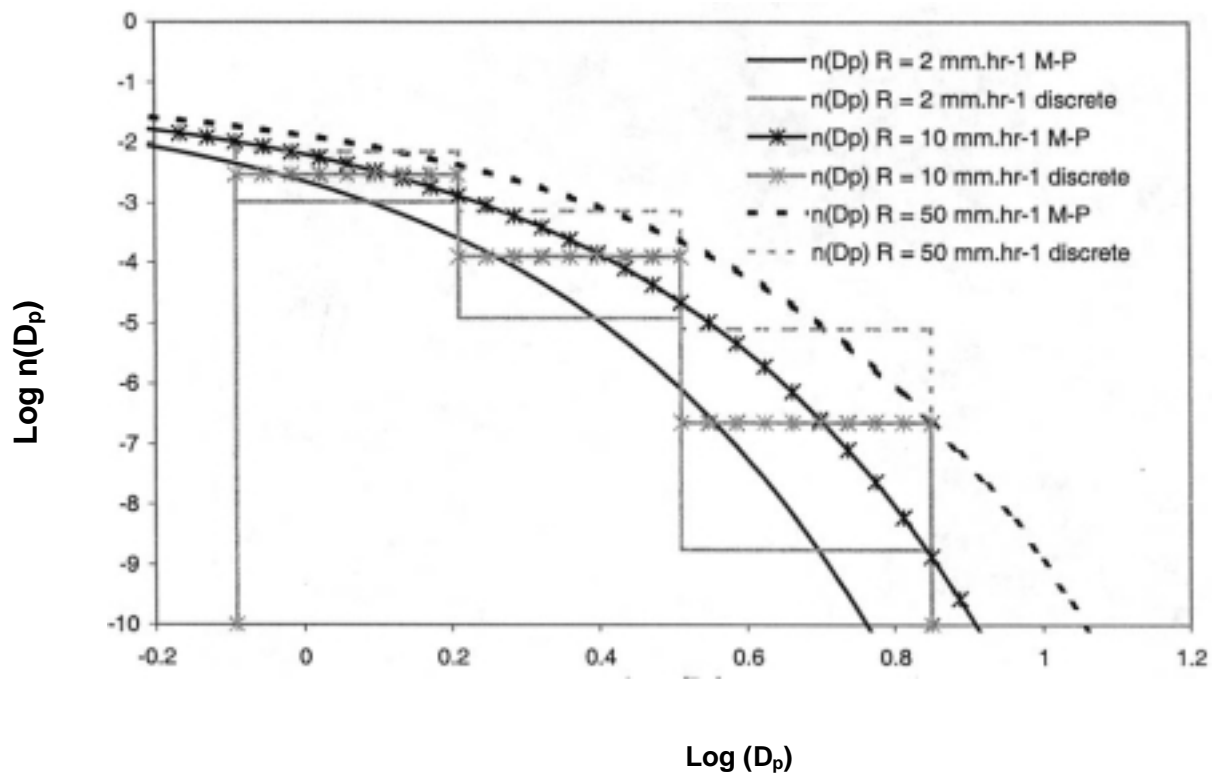
**Figure 10.** Rain Fluxes ( $\text{mm} \cdot \text{year}^{-1}$ ) to sections of the rectangular block by wind direction. a. Forbes Avenue, and b. Fifth Avenue. Figure also shows the fraction of time wind is blowing perpendicular to the face and at an oblique angle from the left and the right. Numbers in gray italics are for data set that includes two large thunderstorms on 6/2/98.



a.

|     |    |     |
|-----|----|-----|
| LS5 | C5 | RS5 |
| LS4 | C4 | RS4 |
| LS3 | C3 | RS3 |
| LS2 | C2 | RS2 |
| LS1 | C1 | RS1 |

b.



| $D_p =$<br>1.25 mm | $D_p =$<br>2.5 mm | $D_p =$<br>5 mm | $D_p =$<br>1.25 mm | $D_p =$<br>2.5 mm | $D_p =$<br>5 mm |
|--------------------|-------------------|-----------------|--------------------|-------------------|-----------------|
| 1.3 1.0 1.3        | 3.1 2.9 3.1       | 5.5 5.1 5.5     | 1.7 1.2 1.7        | 6.3 6.6 6.3       | 11 11 11        |
| 0.0 0.0 0.0        | 0.2 0.0 0.2       | 0.7 0.7 0.7     | 0.0 0.0 0.0        | 0.4 0.4 0.4       | 2.4 1.8 2.4     |
| 0.0 0.0 0.0        | 0.0 0.0 0.0       | 0.3 0.0 0.3     | 0.0 0.0 0.0        | 0.1 0.0 0.1       | 0.4 0.4 0.4     |
| 0.0 0.0 0.0        | 0.0 0.0 0.0       | 0.0 0.0 0.0     | 0.0 0.0 0.0        | 0.0 0.0 0.0       | 0.0 0.0 0.0     |
| 0.0 0.0 0.0        | 0.0 0.0 0.0       | 0.0 0.0 0.0     | 0.1 0.0 0.1        | 0.0 0.0 0.0       | 0.0 0.0 0.0     |

a. Incidence angle =  $0^\circ$ ,  $WS = 1.25 \text{ m}\cdot\text{s}^{-1}$ b. Incidence angle =  $0^\circ$ ,  $WS = 2.5 \text{ m}\cdot\text{s}^{-1}$ 

| $D_p =$<br>1.25 mm | $D_p =$<br>2.5 mm | $D_p =$<br>5 mm | $D_p =$<br>1.25 mm | $D_p =$<br>2.5 mm | $D_p =$<br>5 mm |
|--------------------|-------------------|-----------------|--------------------|-------------------|-----------------|
| 6.5 2.4 6.5        | 17 16 17          | 26 27 26        | 49 41 49           | 66 64 66          | 64 71 64        |
| 0.6 0.0 0.6        | 1.8 1.8 1.8       | 11 9.4 11       | 21 5.8 21          | 44 48 44          | 50 44 50        |
| 0.3 0.0 0.3        | 0.3 1.2 0.3       | 6.8 5.9 6.8     | 31 0.0 31          | 40 46 40          | 41 48 41        |
| 0.0 0.0 0.0        | 0.3 0.0 0.3       | 5.6 5.9 5.6     | 17 0.0 17          | 29 35 29          | 35 42 35        |
| 0.0 0.0 0.0        | 0.3 0.0 0.3       | 3.5 4.7 3.5     | 4.6 0.0 4.6        | 19 25 19          | 24 34 24        |

c. Incidence angle =  $0^\circ$ ,  $WS = 5 \text{ m}\cdot\text{s}^{-1}$ d. Incidence angle =  $0^\circ$ ,  $WS = 10 \text{ m}\cdot\text{s}^{-1}$

| $D_p = 1 \text{ mm}$ |     |     | $D_p = 2 \text{ mm}$ |    |    | $D_p = 5 \text{ mm}$ |    |    |
|----------------------|-----|-----|----------------------|----|----|----------------------|----|----|
| 49                   | 46  | 49  | 49                   | 47 | 49 | 46                   | 45 | 46 |
| 23                   | 19  | 23  | 27                   | 25 | 27 | 31                   | 29 | 31 |
| 15                   | 10  | 15  | 19                   | 17 | 19 | 23                   | 22 | 23 |
| 9.0                  | 5.0 | 9.0 | 14                   | 12 | 14 | 19                   | 17 | 19 |

a. Incidence angle =  $0^\circ$ , reported WS =  $1.25 \text{ m}\cdot\text{s}^{-1}$  at 250 m (equivalent WS at 30 m =  $5.8 \text{ m}\cdot\text{s}^{-1}$ ).

| $D_p = 1 \text{ mm}$ |     |     | $D_p = 2 \text{ mm}$ |    |    | $D_p = 5 \text{ mm}$ |    |    |
|----------------------|-----|-----|----------------------|----|----|----------------------|----|----|
| 49                   | 46  | 49  | 49                   | 47 | 49 | 46                   | 45 | 46 |
| 23                   | 19  | 23  | 27                   | 25 | 27 | 31                   | 29 | 31 |
| 15                   | 10  | 15  | 19                   | 17 | 19 | 23                   | 22 | 23 |
| 9.0                  | 5.0 | 9.0 | 14                   | 12 | 14 | 19                   | 17 | 19 |

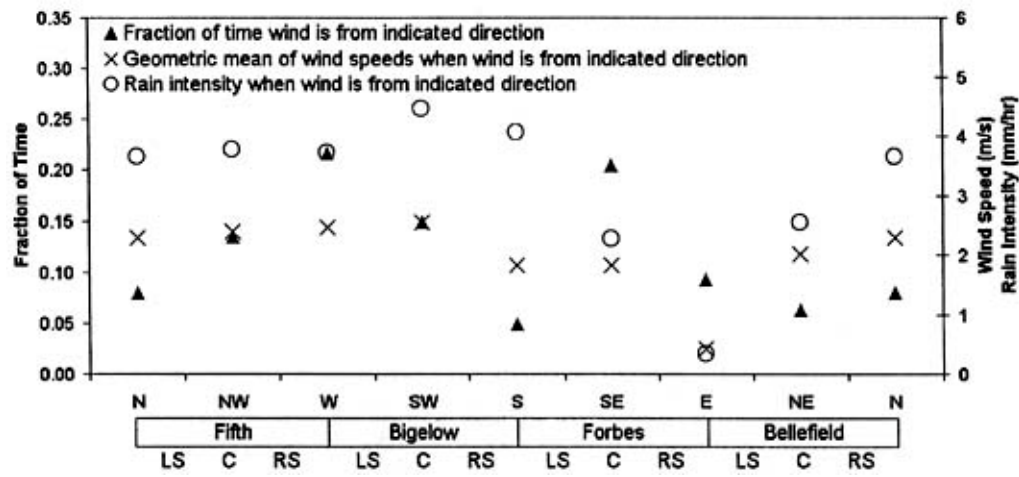
b. Incidence angle =  $0^\circ$ , reported WS =  $20 \text{ m}\cdot\text{s}^{-1}$  at 250 m (equivalent WS at 30 m =  $11.6 \text{ m}\cdot\text{s}^{-1}$ ).

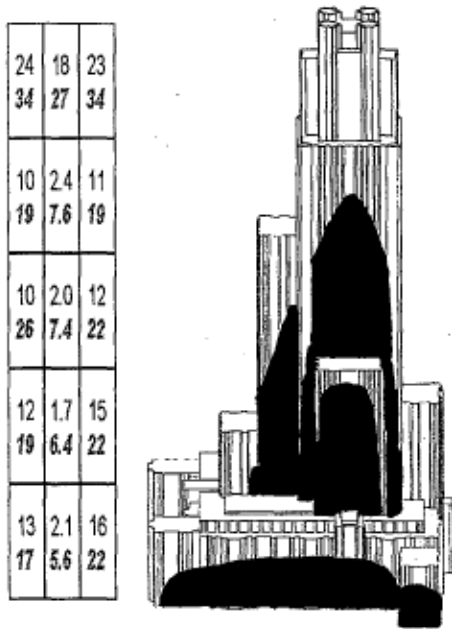
| $D_p =$<br>1.25 mm | $D_p =$<br>2.5 mm | $D_p =$<br>5 mm | $D_p =$<br>1.25 mm | $D_p =$<br>2.5 mm | $D_p =$<br>5 mm |
|--------------------|-------------------|-----------------|--------------------|-------------------|-----------------|
| 7.1 2.1 2.4        | 7.9 4.4 4.1       | 8.6 6.6 5.3     | 13 5.0 3.1         | 16 9.6 8.2        | 18 13 11        |
| 4.3 0.0 0.0        | 3.1 0.0 0.5       | 3.2 1.0 0.5     | 8.7 0.0 0.0        | 8.1 0.3 0.4       | 8.1 2.3 2.6     |
| 5.1 0.0 0.3        | 3.1 0.0 0.0       | 2.1 0.4 0.0     | 11 0.0 0.0         | 6.7 0.3 0.0       | 7.3 0.7 0.0     |
| 5.7 0.0 0.0        | 3.5 0.0 0.0       | 2.6 0.0 0.0     | 12 0.0 0.0         | 7.1 0.0 0.5       | 8.6 0.0 0.0     |
| 4.8 0.0 0.0        | 2.8 0.0 0.0       | 2.1 0.0 0.0     | 9.9 0.0 0.0        | 7.5 0.6 0.0       | 8.3 0.0 0.0     |

a. Incidence angle =  $45^\circ$ , WS =  $1.25 \text{ m}\cdot\text{s}^{-1}$ d. Incidence angle =  $45^\circ$ , WS =  $2.5 \text{ m}\cdot\text{s}^{-1}$ 

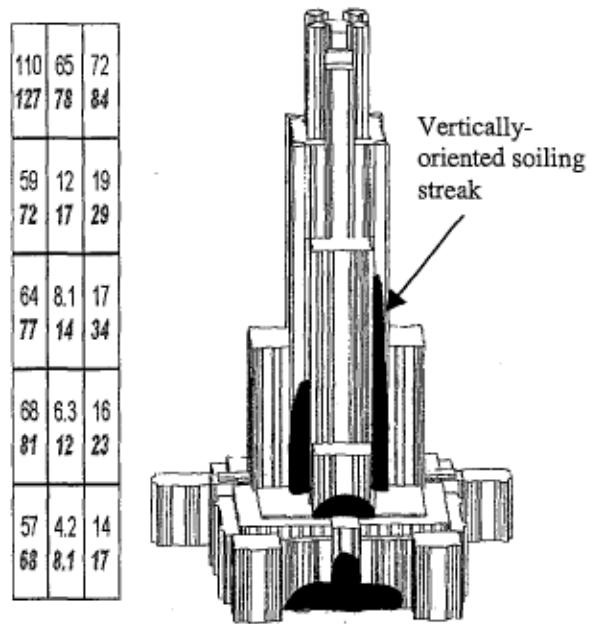
| $D_p =$<br>1.25 mm | $D_p =$<br>2.5 mm | $D_p =$<br>5 mm | $D_p =$<br>1.25 mm | $D_p =$<br>2.5 mm | $D_p =$<br>5 mm |
|--------------------|-------------------|-----------------|--------------------|-------------------|-----------------|
| 37 5.5 7.0         | 37 18 18          | 38 25 22        | 60 16 11           | 92 50 42          | 82 54 47        |
| 34 0.0 0.0         | 23 2.3 1.3        | 23 7.2 5.6      | 45 12 0.0          | 77 20 13          | 70 31 26        |
| 42 0.0 0.0         | 25 0.0 0.4        | 23 3.8 1.9      | 49 19 0.0          | 82 15 11          | 72 30 18        |
| 47 0.0 0.0         | 29 0.0 0.0        | 26 1.5 1.1      | 58 23 0.0          | 83 20 0.0         | 70 31 23        |
| 35 0.0 0.0         | 25 0.0 0.0        | 26 0.0 0.4      | 56 1.2 0.0         | 75 15 0.0         | 64 24 13        |

c. Incidence angle =  $45^\circ$ , WS =  $5 \text{ m}\cdot\text{s}^{-1}$ d. Incidence angle =  $45^\circ$ , WS =  $10 \text{ m}\cdot\text{s}^{-1}$

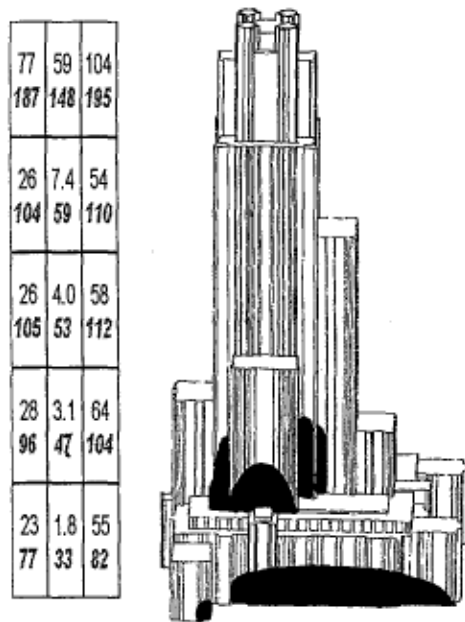




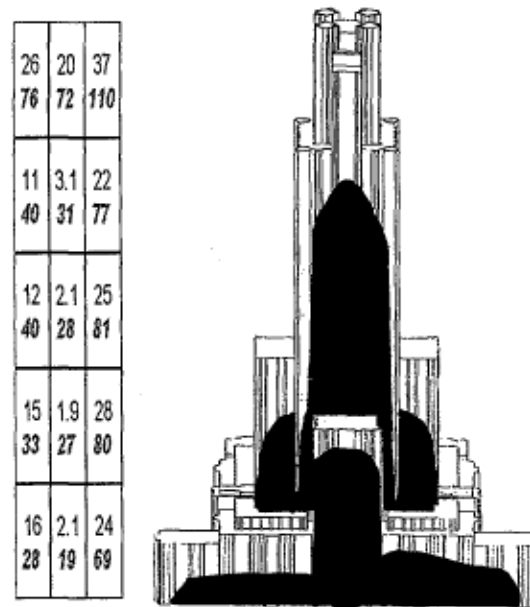
a. Forbes Avenue (Facing SE)



b. Bigelow Boulevard (Facing SW)



c. Fifth Avenue (Facing NW)



d. Bellefield Avenue (Facing NB)

|                           |     |     |                          |     |     |                        |     |     |                         |     |     |
|---------------------------|-----|-----|--------------------------|-----|-----|------------------------|-----|-----|-------------------------|-----|-----|
| 4.0                       | 2.9 | 4.9 | 12                       | 9.5 | 10  | 6.7                    | 5.2 | 7.8 | 0.4                     | 0.4 | 0.4 |
| 4.0                       | 2.9 | 4.9 | 12                       | 9.5 | 10  | 6.7                    | 5.2 | 7.8 | 11                      | 9.6 | 11  |
| 0.8                       | 0.0 | 1.6 | 4.6                      | 0.4 | 2.9 | 4.3                    | 1.9 | 5.9 | 0.2                     | 0.1 | 0.9 |
| 0.8                       | 0.0 | 1.6 | 4.6                      | 0.4 | 2.9 | 4.3                    | 1.9 | 5.9 | 8.8                     | 5.3 | 8.9 |
| 0.9                       | 0.0 | 1.7 | 4.3                      | 0.2 | 2.3 | 4.3                    | 1.7 | 6.2 | 0.3                     | 0.1 | 1.7 |
| 0.9                       | 0.0 | 1.7 | 4.3                      | 0.2 | 2.3 | 4.3                    | 1.7 | 6.2 | 16                      | 5.6 | 12  |
| 0.9                       | 0.0 | 1.9 | 4.6                      | 0.0 | 2.6 | 6.2                    | 1.6 | 9.9 | 0.3                     | 0.1 | 0.1 |
| 0.9                       | 0.0 | 1.9 | 4.6                      | 0.0 | 2.6 | 6.2                    | 1.6 | 9.9 | 7.4                     | 4.8 | 7.3 |
| 0.7                       | 0.0 | 1.6 | 4.8                      | 0.3 | 2.6 | 7.1                    | 1.7 | 12  | 0.3                     | 0.1 | 0.0 |
| 0.7                       | 0.0 | 1.6 | 4.8                      | 0.3 | 2.6 | 7.1                    | 1.7 | 12  | 4.8                     | 3.6 | 5.8 |
| WS=1.25 m•s <sup>-1</sup> |     |     | WS=2.5 m•s <sup>-1</sup> |     |     | WS=5 m•s <sup>-1</sup> |     |     | WS=10 m•s <sup>-1</sup> |     |     |
| m•s <sup>-1</sup>         |     |     |                          |     |     |                        |     |     |                         |     |     |

a. Forbes Avenue

|                           |            |            |                          |            |          |                        |            |          |            |           |            |
|---------------------------|------------|------------|--------------------------|------------|----------|------------------------|------------|----------|------------|-----------|------------|
| 3.3<br>3.3                | 2.4<br>2.4 | 4.8<br>4.8 | 14<br>14                 | 13<br>13   | 22<br>22 | 56<br>56               | 39<br>39   | 68<br>68 | 4.0<br>115 | 4.3<br>93 | 8.6<br>100 |
| 0.8<br>0.8                | 0.0<br>0.0 | 2.0<br>2.0 | 3.3<br>3.3               | 0.4<br>0.4 | 11<br>11 | 20<br>20               | 5.0<br>5.0 | 35<br>35 | 1.7<br>80  | 2.0<br>54 | 6.3<br>62  |
| 0.8<br>0.8                | 0.0<br>0.0 | 2.2<br>2.2 | 3.1<br>3.1               | 0.2<br>0.2 | 11<br>11 | 20<br>20               | 1.7<br>1.7 | 38<br>38 | 1.8<br>81  | 2.0<br>51 | 6.9<br>61  |
| 0.8<br>0.8                | 0.0<br>0.0 | 2.4<br>2.4 | 3.6<br>3.6               | 0.0<br>0.0 | 12<br>12 | 23<br>23               | 0.7<br>0.7 | 43<br>43 | 0.7<br>69  | 2.4<br>46 | 7.1<br>46  |
| 0.7<br>0.7                | 0.0<br>0.0 | 2.0<br>2.0 | 3.2<br>3.2               | 0.4<br>0.4 | 11<br>11 | 18<br>18               | 0.5<br>0.5 | 35<br>35 | 0.3<br>55  | 0.9<br>32 | 6.4<br>34  |
| WS=1.25 m•s <sup>-1</sup> |            |            | WS=2.5 m•s <sup>-1</sup> |            |          | WS=5 m•s <sup>-1</sup> |            |          | WS=10      |           |            |

b. Fifth Avenue